NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

CONSORTIUM FOR ROBOTICS AND UNMANNED SYSTEMS EDUCATION AND RESEARCH (CRUSER)

2022 ANNUAL REPORT

by

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December 2022

Prepared for:
Dr. Thomas Drake
Director, Code 32, Office of Naval Research

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14. ABSTRACT
The Naval Postgraduate School (NPS) Consortium for Robotics and Unmanned Systems Education and Research (CRUSER) provides a collaborative environment and community of interest for the advancement of unmanned systems (UxS) education and research endeavors across the Navy (USN), Marine Corps (USMC) and Department of Defense (DoD). CRUSER is a Secretary of the Navy (SECNAV) initiative to build an inclusive community of interest on the application of unmanned systems (UxS) in military and naval operations. This 2022 annual report summarizes CRUSER activities in its tenth year of operations and highlights future plans.

15. SUBJECT TERMS
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TABLE OF CONTENTS

I. INTRODUCTION

A. BACKGROUND

The Naval Postgraduate School (NPS) Consortium for Robotics and Unmanned Systems Education and Research (CRUSER) provides a collaborative environment and community of interest for the advancement of unmanned systems education and research endeavors across the Navy (USN), Marine Corps (USMC) and Department of Defense (DoD). CRUSER is a Secretary of the Navy (SECNAV) initiative to build an inclusive community of interest on the application of unmanned systems in military and naval operations. Funding for seed research activities is provided by the Office of Naval Research, other activities are funded by a variety of sources. CRUSER encompasses the successful research, education, and experimentation efforts in unmanned systems currently ongoing at NPS and across the naval enterprise.

B. VISION

At the direction of the SECNAV, NPS leverages its long-standing experience and expertise in research and education related to intelligent autonomous systems (IAS) in support of the naval mission. The CRUSER program grew out of the SECNAV's unmanned systems prioritization, and concurrent alignment of unmanned systems research and experimentation at NPS. CRUSER serves as a vehicle by which to align currently disparate research efforts and integrate academic courses across domain and discipline boundaries with the DON Unmanned Campaign Framework DON Science and Technology Strategy for IAS.

CRUSER is a facilitator for the Navy's common research interests in current and future unmanned systems and robotics. The Consortium, working in partnership with other organizations, will continue to inject a focus on IAS into existing joint and naval research and field experiments as well as host specific events, both experimental and educational.

Furthermore, with the operational needs of the Navy and the Marine Corps at its core, CRUSER will continue to be an inclusive, active partner for the effective education of future military leaders and decision makers. Refining existing courses of education and

designing new academic programs is an important benefit of CRUSER, making the Consortium a unique and indispensable resource for the Navy while highlighting the educational mission of NPS. Specific CRUSER goals continue to be:

- Shape generations of naval officers through education, research, concept generation and experimentation in maritime application of robotics, automation, and unmanned systems.

- Provide a source for unmanned systems employment concepts for operations and technical research.

- Provide an experimentation program to explore unmanned system employment concepts.

- Provide a venue for Navy-wide education in intelligent, autonomous systems.

- Provide a DoD-wide forum for collaborative education, research, and experimentation in unmanned systems.

CRUSER takes a holistic approach to address issues related to naval unmanned systems research and employment, from technical to ethical and concept generation to experimentation. A variety of research areas inform and augment traditional technical research in unmanned systems, and aid in their integration into fleet operations.

C. MANAGEMENT

CRUSER is organized as an NPS research project except with a more extensive charter than most reimbursable projects. It has both an oversight organization and coordination team. The Director, with the support of a lean research and administrative staff, leads CRUSER and executes the collaborative vision for the Consortium. The Director encourages, engages, and enhances on-campus efforts among all four graduate schools and existing centers and institutes. Faculty and students from all curricula with an interest in the development of unmanned systems are encouraged to contribute and participate. Furthermore, the CRUSER advisory group (CAG), consisting of the CRUSER directors, Dean of Research, warfare chairs and on-campus senior officers from

each military service, provides high-level direction to balance academic, S&T and warfighting perspectives. This group ensures that the Fleet and its operations remain a primary consideration in CRUSER activities to include the selection of activities supported by CRUSER.

D. FINANCIAL

The 2022 CRUSER Program received $3,900,000 from ONR (N0001422WX00617, N0001422WX02004) in mid-January, with a period of performance end date of 31 Dec 2022. As of the date of 12 December 2022, the funding is 64.7% expended, 35.1% obligated/encumbered, with an unspent balance of 0.2%.

II. SEED RESEARCH PROJECTS

The CRUSER Seed Research Program (SRP) is a critical aspect of how CRUSER achieves this objective. The program provides an environment for students, faculty, and staff to collaborate both internally and externally with the common goal of accelerating the development and fielding of unmanned systems across the DON. Furthermore, the SRP functions as an incubator, providing initial support for the NPS community to explore new, relevant concepts with the potential to transition to externally supported NPS research program.

CRUSER research provides an authentic academic experience for NPS students within the many fields that constitute Intelligent Autonomous Systems (IAS) science and technology. CRUSER continues to support a wide diversity of research topics, "from technical to ethical, from concept to experiment". CRUSER prioritizes support for seed projects that have a clear transition path for follow-on external support, e.g., research grant support, fleet investment, etc.

CRUSER supports both fundamental research (both basic and applied), "the results of which ordinarily are published and shared broadly within the scientific community,"1 and development, design, production, and product utilization efforts, the results of which ordinarily are restricted or classified or national security reasons. Table 1 summarizes the 15 CRUSER seed research projects for 2021 and the following subsections are detailed summaries of each project.

Table 1: 2022 CRUSER Seed Research Projects

	Principal Investigator(s)	**Project Title**
1	Prof. Troy Ansell	Extending the Endurance of Multi-rotor UAVs with Boron Nitride Nanotube (BNNT)-based Piezoelectric Composites
2	Prof. Leo Blanken Cecilia Panella Michael Stevens	COTS Unmanned Systems and Partner Force Innovation
3	Prof. Christopher Brophy Prof. Joshua Codoni	Counter Aerial UxS Munition Delivery System

4	Prof. Abe Clark Prof. Isaac Kaminer	Operational Planning Simulations of HPM-equipped Swarm Engagements
5	Prof. Nick Dew Prof. Imre Balogh	Interactive Synthetic Environment (ISE) to Evaluate Zero-Carbon UAS Launch Platforms in the Arctic
6	Kristen Fletcher Eric Hahn Marina Lesse	Advancing Clarity: Analysis of UxS Legal Questions
7	Prof. Britta Hale Prof. Douglas Van Bossuyt	UxS Manned/Unmanned Secure Teaming
8	Prof. Douglas Horner Prof. Geoffrey Xie Prof. Ruriko Yoshida	BION - Behavior Integration and Optimization for Networked Control Systems (NCS)
9	Prof. Kevin Jones Prof. Vladimir Dobrokhodov Dr. Paul Leary Prof. Kevin Smith	Aqua-Quad Sensor Integration and Participation in Trident Warrior 2022
10	Prof. John Joseph Yi Chao (Seatrec Inc) John Ryan (MBARI)	Persistent Smart Acoustic Profiler (PSAP)
11	Prof. Isaac Kaminer Aurelio Monarrez	Collaborative Hyper-Enabled Operations in Contested Environments (CHOICE)
12	Prof. Joseph Klamo Prof. Jarema Didoszak Prof. Young Kwon	Proof-of-concept: Achieving Free Propulsion for Flexible UUVs Using Vortical Wakes
13	Prof. Sean Kragelund Prof. Matt Feemster (USNA) Prof. Violet Mwaffo (USNA) CDR Paul Frontera (USNA)	SURFACE: Swarming USVs and Resilient Formations Against Contested Environments
14	Prof. Mollie McGuire Aurelio Monarrez	Human-Autonomy Teaming: Control of Multi-Domain UxV's
15	Prof. David Ortiz-Suslow Ryan Yamaguchi	sUAS-based Remote Sensing of Surface Waves and Breaking using an EO/IR Camera System
16	Prof. Robert Semmens Kristen Fletcher Prof. Douglas Van Bossuyt Prof. Britta Hale	Who Makes Johnny 5 Come Alive? Using Diverse Perspectives to Drive Requirements for Human-Robot Teams

A. EXTENDING THE ENDURANCE OF MULTI-ROTOR UAVS WITH BORON NITRIDE NANOTUBE (BNNT)-BASED PIEZOELECTRIC COMPOSITES

Participants

- Principal Investigator (PI): Troy Y. Ansell <troy.ansell@nps.edu>
- Students: ENS Anna Sewall <anna.sewall@nps.edu>

Major Goals

Multi-rotor drones (UAVs) offer greater maneuverability, ease of use, and cost effectiveness in design as compared to fixed-wing UAVs. Multi-rotor drones may also have increased relative payload capacity depending on the number of rotors when compared to their fixed-wing counterparts. These advantages come at the cost of decreased cruising speed, range, and endurance. Increasing the endurance of multi-rotor UAVs would result in increased operational range. An obvious first choice for increasing UAV range is to increase battery capacity. This comes with a huge downside; however, as increasing battery capacity means increasing the UAV weight requiring increased power for thrust. An alternative is to harvest vibrational energy generated by the rotors during flight. To accomplish this, piezoelectric materials can be attached to the frame of the UAV and connected to the battery for partial recharging in-flight. The piezoelectric material itself should be lightweight without sacrificing energy harvesting volume, i.e., a polymer like polyvinylidene fluoride – trifluoroethylene (PVDF-TrFE) instead of heavier ceramic piezoelectrics. Because PVDF has relatively low piezoelectric coefficients compared to piezoceramics, polymer-matrix piezo-composites will be fabricated with PVDF-TrFE as the matrix material.

The additive must also be piezoelectric to increase the active volume. A prime candidate for this is boron nitride nanotubes (BNNT). This research seeks to integrate BNNTs into PVDF-TrFE to form functional piezo-composites, which can harvest vibrational energy generated in-flight and in-turn increase the endurance of multi-rotor UAVs. This integration will be accomplished via stereolithography (SLA). PVDF-TrFE will first be dissolved; BNNTs will be mixed into the dissolved polymer; then a photopolymer will be added to the mixture. The mixture will then be printed in SLA printer. Piezoelectric properties will be measured. Printed harvesters will then be attached to a UAV and power output measured. Long-term goal will be to fabricate BNNT mats without the polymer as the piezo-coefficient-to-weight ratio is likely to be much higher for the BNNTs alone.

Accomplishments:

- Full budget has been executed and the processing and experimental setups completed.
- PVDF-TrFE has been dissolved and mixed with Formlabs Clear resin.
- Piezo-composites without BNNTs have been printed in various geometries (refer to Figure 1).

Next Steps:

- Mix in BNNTs, print, and electrically pole composites. This should be completed by the end of January 2023.

- Measure piezoelectric properties of composites. This should be completed by the end of February 2023.
- Attach harvesters to UAV and measure power output. Plan on conducting and completing these tests by the end of FY23.

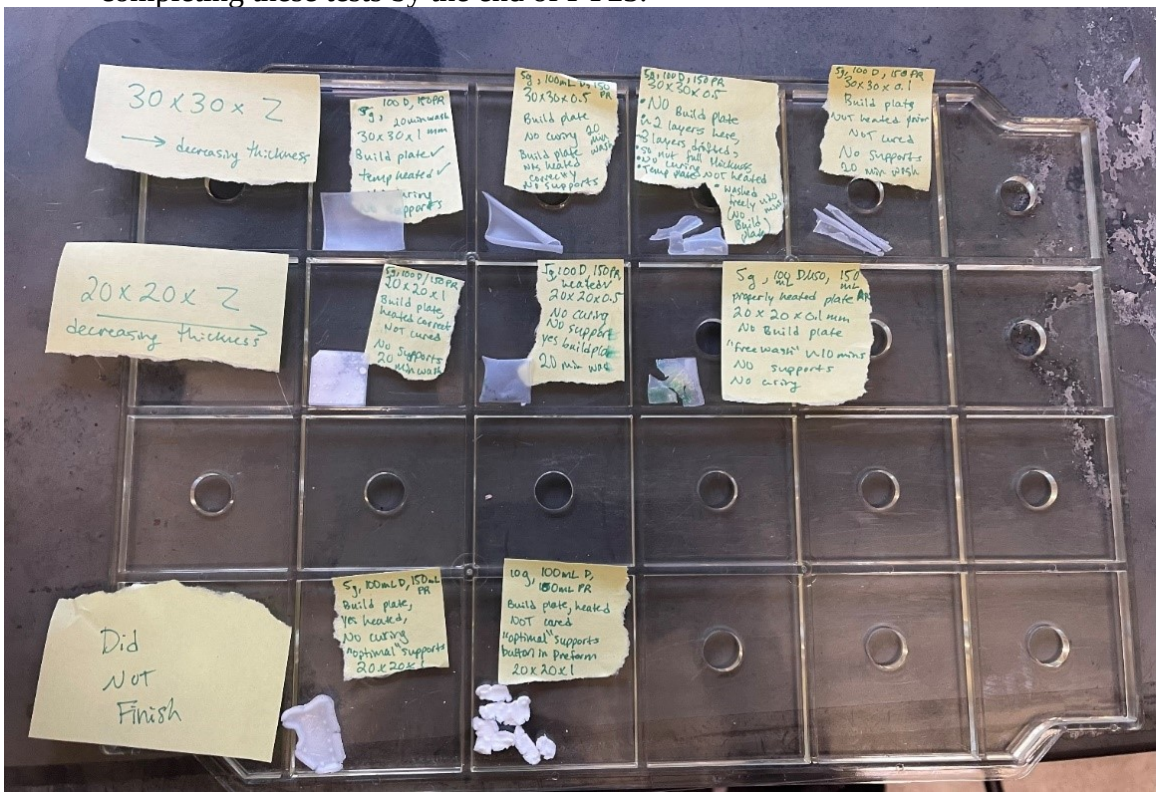

Figure 1: Initial trial prints. Dimensions of samples in mm. Geometry with the highest promise is 20 x 20 x 1 mm.

Education:

- One student thesis (ENS Sewall) supported and currently in progress.

Dissemination:

- Plan on submitting results of project to MRS Communications.

B. COTS UNMANNED SYSTEMS AND PARTNER FORCE INNOVATION

Participants

- Principal Investigator (PI): Leo Blanken ljblanke@nps.edu
- Co-PIs: Cecilia Panella
- Students:
    - Colonel Ernest Jadloc (Philippines Army)
    - Major Joel Bonavente (Philippines Marine Corps)

Major Goals

The first phase of this project focused on the work of Romulo Dimayuga's thesis project, entitled "Commercial-Off-the-Shelf Drone Design: A Rapid Equipage Alternative for Force Recon Companies." Major Dimayuga, a Marine from the Philippines, came to NPS with the passion to fill a capability gap for his home unit – an affordable, sustainable, unmanned aerial system that would provide short-range reconnaissance tailored specifically to the tactical needs of the Filipino Force Recon Marines. His units needed such a "home grown" system, because the American systems (Raven, Puma) were controlled by higher echelons and were frequently not available for the Marines at the Company level. Working with NPS faculty and the campus RoboDojo, Romulo sought to design a basic prototype of such a system.

The second phase of the project extended the model created by Major Dimuyaga. This involved two more thesis projects focused on the Philippines military. The second was Major Joel Bonavente's "Proposed Design of a Low-Cost, Counter-Radio-Controlled Improvised Explosive Device for the Philippine Marine Corps' Rapid Equipage" (December 2022). The third was Colonel Ernest Jadloc's "Safe and Effective Close Air Support: Leveraging COTS Products for Maneuverable Aerial Identification, Friend or Foe" (June 2022). These projects continued the theme of leveraging commercial-off-the-shelf components to enable partner force innovation.

Following from MAJ Dimayuga's project, RDFP student Colonel Ernest Jadloc (Army of the Philippines, JUNE '22) refine the prototype by adding a new payload to it to address a specific tactical use case: identifying the location of friendly forces for close air support in dense foliage. The goal of his thesis project included working towards having this system tested in Armed Forces of the Philippines' joint exercises as a pathway towards eventual adoption. COL Jadloc was able to successfully test his UAS with the assistance of NPS faculty. COL Jadloc was able to coordinate with two other CRUSER-supported students, MAJ Pat Foley and MAJ Peter (Count) Harris, after his return to the Philippines on opportunities for further development.

MAJ Foley and MAJ Harris (DEC '22) are ARSOF students currently in Defense Analysis who have developed a secondary support tool called iSHARE to assist with (a) the future of US enablement of partner forces and (b) steady-state activities within the broader context of Great Power Competition (GPC). More specifically, their work enables and leverages partner force capabilities for the future information environment. Their deliverable visual COP with data aggregation capabilities, coupled with M.S. Teams-like functions and expandable to include OSINT tools. In alignment with CRUSER Seed Research goals of identifying and leveraging potential transition partners,

their work was partially sponsored by First Special Forces Command (1SFC) for development and implementation. They completed a tech demonstration and data validation exercise in the Philippines and Mongolia as a part of their research. 1SFC has committed to expanding this project in FY23 as a collaborative partner with NPS. MAJ LaMarke Patterson is an ARSOF student in Defense Analysis who developed Project POWRS, which focuses on combining a suite of edge devices for use at the tactical level, stored on a cloud network, and accessible to agencies and joint partners in one robotic, self-contained device for IAS employment. POWRS leverages the advancements in COTS technology and cutting-edge third-party tools to provide dominance of the information environment. This tool utilizes a 360-degree camera to conduct geographic surveillance, with future iterations of the project designed to incorporate night vision, thermal imaging, biometrics collection, and incorporation with in-vehicle Command and Control (C2) capabilities for American operators and partner forces to increase awareness of the operating environment prior to physical engagement. MAJ Patterson's work also includes substantive analysis on the intersection of artificial intelligence, ethics, and unmanned systems for operational employment, resulting in follow-on research considerations for multiple components across the joint force. MAJ Patterson has also spearheaded three separate CRADA agreements as a part of his research in order to securely and safely incorporate private company technology into his project. In accordance with CRUSER guidelines, MAJ Patterson received partial sponsorship from SOFWERX for the implementation and future development of his work in future phases. SOFWERX is committed to continuing with this project in FY23, in collaboration with multiple CRADA partners and NPS.

LT Julian "Fish" Salmon is a Naval Intelligence Officer graduating in December 2022 from the National Security Affairs Department. His work exists primarily at a higher classification, but the core of his thesis examines how smart city technologies (networked sensors, IoT, UTS, machine learning/AI, biometric data/PII federation) have impacted SOF's ability to conduct Sensitive Activities within East Asia. SOF's ability to effectively conduct PE is critical to OPLAN execution and the Competition Continuum. As smart city technologies that leverage unmanned systems and artificial intelligence continue to become more advanced, integrated, and widespread across the AOR, the likelihood of SOF entities incurring increased risk of compromise (mission and personnel) will increase. Fish's research addressed how and where China has supported smart city development in other countries and regional smart cities present the most concern (non-permissiveness) for future SA in East Asia.

Thematically, we posit that the U.S. Department of Defense faces three key challenges in working with partners in the GPC environment. First, building partner capacity is becoming even more important for American national security. Second, the United States can no longer afford to give large amounts of expensive military equipment to all the partner nations who it wants to influence. Third, there is a growing disconnect between the type of high-tech weapons and systems that are useful for the U.S. military and the lower-tech security needs of many allies and partners. Using grassroots, collaborative innovation to develop cost-effective, sustainable,

Education:

Completed Thesis Projects:

- Dimayuga, Romulo. December 2020. "COTS DRONE DESIGN: A RAPID EQUIPAGE ALTERNATIVE FOR FORCE RECON COMPANIES."
- Jadloc, Ernest. June 2022. "SAFE AND EFFECTIVE CLOSE AIR SUPPORT: LEVERAGING COTS PRODUCTS FOR MANEUVERABLE AERIAL IDENTIFICATION, FRIEND OR FOE."
- Bonavente, Joel. December 2022. "PROPOSED DESIGN OF A LOW-COST, COUNTER-RADIO-CONTROLLED IMPROVISED EXPLOSIVE DEVICE FOR THE PHILIPPINE MARINE CORPS' RAPID EQUIPAGE."
- Foley, Patrick and Harris, Peter. December 2022. "CLOSING THE TECHNOLOGY GAP: PARTNER FORCE DIGITAL TOOLS FOR INFORMATION ADVANTAGE. PROJECT I-SHARE - INFORMATION SHARING AND HOSTING ADVANCED REMOTE ECOSYSTEM ASSESSMENTS."
- Patterson, LaMarke. December 2022. "POWRS: PERSISTENT OUTWARD RECONNAISSANCE SYSTEM."
- Salmon, Julian. December 2022. "UBIQUITOUS VISION: SENSITIVE ACTIVITIES IN DATA DRIVEN ENVIRONMENTS."

Dissemination:

- The project was briefed to Deputy CG of US Army Pacific Command (MG Johnathan Braga), who is now the CG of US Army Special Operations Command.
- The project was briefed to the Commanding General of the US Army John F Kennedy Special Warfare Center and School (MG Patrick Roberson).
- An article was published by Romulo Dimayuga, Leo Blanken, and Kristen Tsolis in *War on the Rocks*: "Making Friends in Maker Spaces: From Grassroots Innovation to Great-Power Competition."
    - Available at: <https://warontherocks.com/2021/01/making-friends-in-maker-spaces-from-grassroots-innovation-to-great-power-competition/>
- An article was published by Ernest Jadloc, Leo Blanken, and Kevin Jones in *Small Wars Journal*: "Helping Partners Help Themselves Through Grassroots Innovation."
    - Available at: <https://smallwarsjournal.com/jrnl/art/helping-partners-help-themselves-through-grassroots-innovation>

Transition:

Adapting the current security force assistance activities of American advisors — especially special operations forces — to foster and empower partner forces would be a potent mechanism to foster such tailored solutions. Further, these home-grown capabilities would establish crucial "buy in" from the end-user while also building stronger relationships with U.S. partners. The technology is also readily available. The commercial market is often leaping ahead of the defense sector in producing ready-made tools for many of the functions that smaller militaries require. From hardware to software, the private sector keeps refining, miniaturizing, and productizing the

components that can be modified or repurposed for security applications. Unmanned systems are the perfect class of projects as they are universally desired, there is growing competition in this space by GPC competitors, and there is a rich COTS landscape to draw from.

These students' work demonstrates the viability of designing and building a prototype to basic military specifications by a user who had no technical expertise. These students relied almost solely on open-source information, the RoboDojo, and minimal funding. This experience shows that a solution to a capability gap need not be expensive and exquisite. The solution might rather be low-cost and bottom-up. Not only did the Philippines military students find solutions to their own problems, but the method of such a solution can hopefully "trickle-up" to the broader military organization by sparking wider innovation networks and activity across the Armed Forces of the Philippines. Given this, what would successful adoption and integration look like? We think it would work in three inter-locking components.

a. Doctrinal Adoption

The first goal would be to work with the most relevant elements of the U.S. Joint Force in regard to Security Force Assistance. These reside within the US Special Operations Forces (USSOF) community. US Army Civil Affairs is an especially attractive partner here. We have, through our Defense Analysis students, direct access to Civil Affairs leadership.

b. Synchronizing with Relevant Lines of Effort

Working with partner forces spans many existing lines of effort and funding streams across the inter-agency. These include Building Partner Capacity (BPC) activities, Security Force Assistance (SFA), Foreign Internal Defense (FID), as well as foreign military sales and various Department of State (DoS) efforts. Research and engagement must be done to identify, coordinate with, or at least deconflict with all such relevant efforts.

c. Leveraging International Professional Military Education Students

The Naval Postgraduate School is a perfect place to host (or at least participate in) many of these projects. Programs such as the Regional Defense Fellowship Program (RDFP), which funds students from many partner nations to NPS and other US professional military education (PME) institutions has already expressed interest in coordinating its selection and support of partner force students with grassroots innovation projects. This would build on an existing relationship and funding source, as these students were funded to attend NPS though the RDFP program.

C. COUNTER AERIAL UXS MUNITION DELIVERY SYSTEM

Participants

- Principal Investigator (PI): Christopher Brophy cmbrophy@nps.edu
- Co-PIs: Joshua Codoni joshua.codoni@nps.edu (Thru 2/1/22)
- Students: LT Thomas Hill (591) and LT Alex Sherenco (591)

Major Goals

A growing problem facing national security revolves around inexpensive, easily manufactured drones. Sophisticated software can link drones into swarms and inflict heavy damage on the United States and her allies' assets, while rudimentary drones could also be used by terrorists to strike civilians from afar. The current research program focuses on using low-cost and readily available commercial off the shelf (COTS) components to develop a rapid-response solid rocket motor payload delivery vehicle capable of navigation to a pre-defined "handoff" point in space. At the "handoff" condition, the payload delivery vehicle releases gravity-fed guided submunitions, which use a bird-of-prey approach, to engage and disable detected unmanned aerial system threats with a non-lethal "kill" mechanism, such as entanglement. The benefits of this approach include using many cheap COTS components intended for amateur rocketry and hobbyist robotics systems, as well as additive manufacturing techniques to integrate a low-cost platform that is a more symmetrical response to aerial unmanned system swarm threats. The greatest challenges include integrating many COTS components that were intended to function in various other environments into a single, reliable, and capable tactical system. These challenges involve workforce development and training through supporting DOD Officer's Master's Thesis work in many areas of interest, including propulsion; aerodynamics; guidance, navigation, and control; systems integration; and programming (GNC, neural networks for threat detection. The system also utilizes reliable and proven technology in the form of a solid rocket motor booster, which has a plethora of benefits including simplicity, storability, and rapid-response capabilities.

Accomplishments:

The research areas of CY22 were directed at delivery vehicle development, high-Mach deployment dynamics, and submunition improvements. The flight testing with the use of Raspberry Pi B and Bosch BNO055 INS systems for guidance and control revealed erratic noise issues associated with I2C communication errors due to clock stretching on each unit. The associated problems were not observed with Arduino units and demonstrates the limitations with what microproccessors are selected for GNC purposes. All of the image processing performed on Raspberry Pi units on targeting hub as well as the individual submunitions did not display any errors.

Key accomplishments related to the submunitions are best described in the theses by LT Alex Sherenco. Vehicle improvements by LT Tom Hill and highlights of LT Sherenco's contributions are summarized below.

- Six test flights were performed. Three with a dedicated munition deployment compartment and three of the delivery vehicle and targeting hub.
- Improved understanding of inherent vehicle roll damping challenges and implementation of grid fins for aerodynamic breaking coupled with conventional

control surfaces for roll control. Selection of a bank-to-turn control strategy for roll-to-pitch plane operation.

- 6 DOF model of flight system developed
- Improved vehicle (sled) separation mechanism through the introduction of frangible bolts (4) and additive manufactured coupling to improve vehicle stiffness and allow for controlled separation at higher flight Mach numbers and aerodynamic loads.
- Implemented and verified a flight telemetry system for transmission of critical flight parameters to ground station during tests.
- Design and incorporation of a Marman clamp for upper vehicle recovery joint to prevent undesired deployment of recovery parachute during vehicle separation event.
- Tracking of multiple submunitions via a near-IR focal plane to determine radial and directional information such that semi-active guidance can be transmitted to submunition during the initial descent towards targets.

Figure 2: Rapid-response vehicle flight vehicle and exposed submunition on launch rail

Figure 3: Launch of delivery vehicle with inset of submunition ejection at apogee

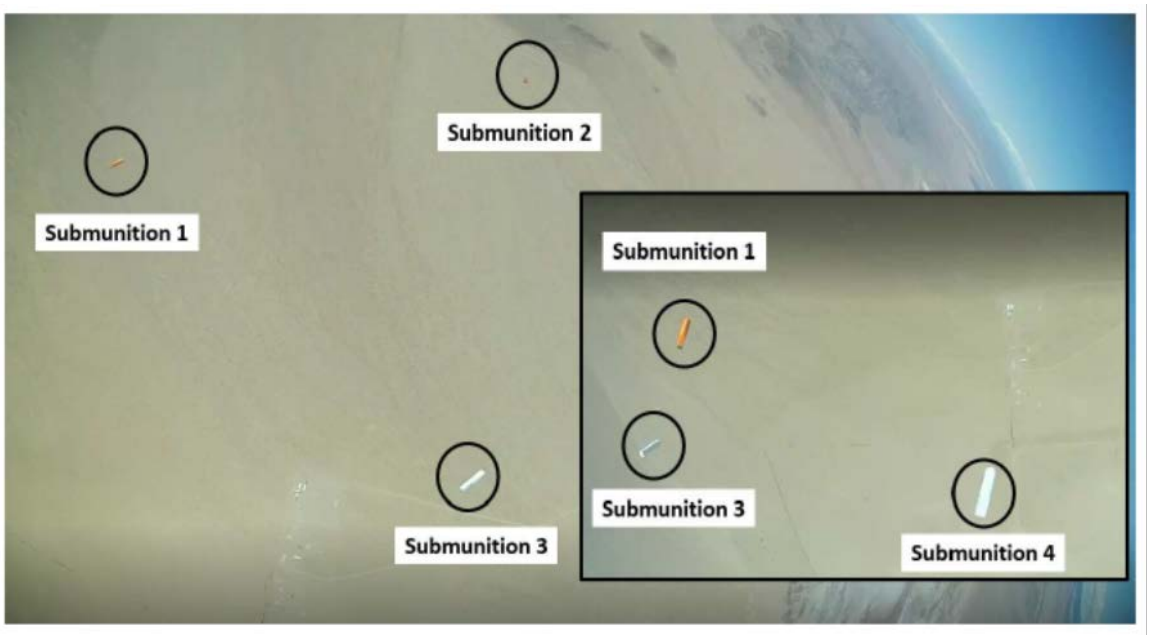

Figure 4: Initial view of submunitions immediately after ejection at apogee

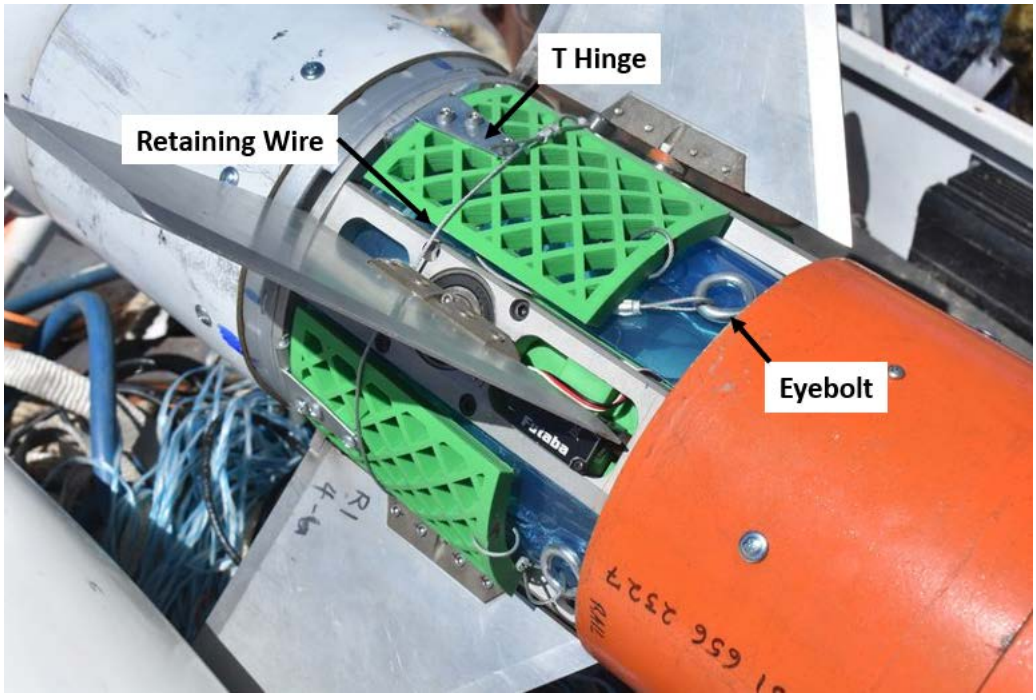

Figure 5: Incorporation of grid fin aero-deceleration for improve image stability during targeting

Education:

- Sherenco, A. *Design, Deployment, and Guidance of Submunitions from a Rapid-Response Vehicle*, Naval Postgraduate School, 2022.
- Hill, T. *Implementation of Canard Control and Grid-Fin Decelerators on a Rapid Response Payload Delivery Vehicle.* Naval Postgraduate School, Exp. Dec 2023.

- ME4704 Tactical Missile Design

Dissemination:
At this time, no public dissemination of this work has occurred, and presentations have been limited to thesis briefs and presentations to visitors who share an interest in this technology. Due to recent successes, it is expected that this work will be presented at the next AIAA Aviation conference pending any approval processes that need to occur.

Collaboration and Partnership:
Discussions have occurred with ONR representatives and other agencies such as the US Army West Point academy to explore synergistic activities, but only in a precursory manner. Dr. Carson Vogt at NPS has been involved with the programming of the Arduino and Raspberry Pi units as well as the image processing discussions. He has also co-advised LT Alex Sherenco with her thesis.

Transition:
A proposal was resubmitted to US TRANSCOM for FY23 funding that would have involved using the primary vehicle for a payload delivery system versus the delivery of the submunitions. Unfortunately, this proposal was not successful and the reviews recommended to find a more appropriate transition partner.
We also expect to contact the Strategic Concepts Office to determine if they have an interest in continuing the development and maturation of the primary vehicle for the rapid-deployment aspects of the system which would include the use of adaptive optimized guidance. Faculty at the West Point academy have continued their interest and are working towards a similar capability that may be able to utilize funding from the US Space Command for a joint NPS/West Point research initiative to continue the development of the flight system for payload deployment purposes.

D. OPERATIONAL PLANNING SIMULATIONS OF HPM-EQUIPPED SWARM ENGAGEMENTS

Participants

- Principal Investigator (PI): Abe Clark <abe.clark@nps.edu>
- Co-PIs: Isaac Kaminer
- Students: Major Michael Wish (USMC), LT Nathan Redder (USN).

Major Goals

The key idea of this project was to apply previous work on modeling and optimization of counter-drone simulations to study high-power microwave (HPM) weapons. HPMs are an emerging anti-drone weapon, which use high-energy beams of electromagnetic radiation to disrupt motors, electronics, or other components on various targets, including enemy drones or other unmanned vehicles. HPMs will emit a characteristic radiation pattern (as shown in the left figure below) which will correlate with an effectiveness of disrupting and disabling incoming enemy drones. The potential scenarios could be arbitrarily complex, as shown in the right figure below), including airborne or ground-based HPM weapons. Computer simulations are therefore a very useful tool for developing optimal tactics and understanding performance limitations of these weapons.

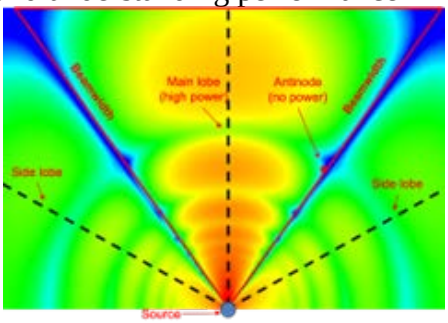

Figure 6

Figure 7

Our previous work involved agent-based simulations of large-scale adversarial autonomy scenarios. Drone trajectories were computed using various swarming and cooperation strategies, and weapons were modeled using spatially dependent atttrition functions. Our major goals in this project were therefore to:

1. **Modify existing simulations** to include weapons models and drone dynamics that were maximally relevant to DoD researchers and mission planners using HPM weapons as an anti-drone defense strategy;
2. identify and analyze any **new fundamental research questions** that emerged from these changes; and
3. use our results to open **new sources of collaboration** with other DoD entities and to secure **ongoing funding** from external sources.

Accomplishments:
Our accomplishments are summarized in accordance with the three major goals listed above. The work for this project was primarily carried out as a part of the thesis work of Major Michael Wish (USMC). Maj Wish graduates in Dec 2022 and is headed to the Naval Academy as an instructor. Additional relevant results were included in LT Nathan Redder's (USN) thesis.

1. **Modify existing simulations:** After discussion with the Marines at Ground-based Air Defense (GBAD) at Quantico, we decided to study the scenario of 1 to 2 tube-launched HPM-equipped drones defending against a small force of enemy drones who were attacking an HVU. The HPM-equipped drones would have short-range, deep-magazine HPM weapons, meaning existing simulations should be modified such that weapons were very effective but only had effectiveness over very short distances (unlike conventional ballistic weapons). Additionally, the HPM-equipped drones would use bank-to-turn dynamics, which meant changing the mathematical way that the defender trajectories were modeled. Existing simulations were modified to include these characteristics.
2. **New fundamental research questions:** After modifying the existing simulations to include characteristics specific to HPM weapons (short range, very effective) and HPM-equipped drone flight dynamics (bank-to-turn), several new fundamental research questions emerged.

   The first new research question arose from the fact that the weapons were very short range, meaning that the optimal tactics involved partitioning the enemy drones into subsets (one for each defender drone) and then determining an optimal order to visit many moving targets. The partitioning problem is very challenging, but LT Redder's thesis involve a quantitative study of heuristic ways to decompose the attackers into subsets for each defender. Maj Wish focused on how one should determine the optimal attacker order, mapping it onto the classic "Traveling Salesman Problem" (TSP). He showed that TSP algorithms can be applied under very simple assumptions, but that machine learning offers a much more promising approach to determining the best order of engagement.

   The second new research question involved how to optimize defender flight paths using bank-to-turn dynamics. Although previously used approaches, which represented the defender paths using Bernstein polynomials, are possible with bank-to-turn dynamics, these approaches require solving a constrained optimization problem. Maj Wish reformulated the defender trajectories in a way that allows for solving an unconstrained optimization problem. This has

significant advantages in some cases, such as using Monte Carlo methods to find a global optimum instead of using local, gradient-based search methods, which often get stuck in local optima. Further details can be found in Maj Wish's thesis, soon to be published by Dudley Knox library.

3. **New sources of collaboration / ongoing funding:** During the period of performance for this project, the PI made two visits to Naval Surface Warfare Center Dahlgren Division (NSWCDD), with technical point-of-contact (TPOC) Spencer Beloin; one visit to GBAD at Quantico, TPOCs Michael Wade and Tom Foddrill; and one visit to ONR to visit Ryan Hoffman, who runs the HPM research program there. Results were shown to these entities and feedback was solicited. One outcome of these interactions is that future work will include antenna modeling directly in the workflow of the simulations, such that specific HPM antennas can be compared directly in our simulation framework.

Education:
Student thesis supported by this project are below. Both are not yet published but will be later this month (Dec 2022).

Wish, M. J. (2022). "Operational Planning and Optimization of Small Domain Swarm Defense Strategies" Naval Postgraduate School, Monterey, CA.

Redder, N. C. (2022). "Trade-off Analysis of Large-scale Swarm Engagements." Naval Postgraduate School, Monterey, CA.

Dissemination:
No publications yet, but both student thesis will be written up into journal papers in 2023.

Collaboration and Partnership:
As described above, this work was done in partnership with HPM researchers at NSWCDD, TPOCs Spencer Beloin and John Robie; Marines at GBAD, TPOCs Michael Wade and Tom Foddrill; and input from Ryan Hoffman, program manager for the HPM program at ONR.

Transition:
Ryan Hoffman supported our Naval Research Program proposal for ongoing work on this project, which we currently have funded through June 2023. We fully expect future funding from his program. Additionally, this work led to insights into our ongoing work for Marc Steinberg's "Science of Autonomy" program at ONR. Results from this year and last year's CRUSER efforts were instrumental in securing funding from this program.

E. INTERACTIVE SYNTHETIC ENVIRONMENT (ISE) TO EVALUATE ZERO-CARBON UAS LAUNCH PLATFORMS IN THE ARCTIC

Participants

- Principal Investigator (PI): Dr. Nick Dew, ndew@nps.edu
- Co-PI: Dr. Imre L. Balogh, ilbalogh@nps.edu
- Key Personnel:
  - Christian Fitzpatrick, christian.fitzpatrick@nps.edu
  - Kristen Fletcher, kristen.fletcher@nps.edu
  - Marina Lesse, marina.lesse@nps.edu
- Students:
  - Captain Tim Socha, USMC Student, Department of Defense Management
  - Rebecca Grippo. Law Student, Roger Williams University School of Law

Major Goals

Figure 8: HAV Airlander 10 Heavier-Than-Air Aircraft, Source: HAV website at https://www.hybridairvehicles.com

The Arctic Ocean has lost nearly a million square miles of ice since the 1980s and it is projected to be ice free in the summer months by mid-century. This poses an operational problem for the US Navy and US Coast Guard as they provide persistent naval presence around the globe. As the Arctic ecosystem changes, and maneuverable waters increase with ice melt, this problem becomes more challenging to manage. To address this issue, Hybrid Air Vehicles' (HAV) Airlander 10 was analyzed to potentially enable a further naval presence in the Arctic. The Naval Postgraduate School (NPS) has a Cooperative Research and Development Agreement (CRADA) with HAV, the United Kingdom (UK)-based, heavier-than-air aircraft development company. Our CRADA was established to specifically investigate military applications of the Airlander 10. Our CRUSER research our first effort to support HAV.

Because the Airlander 10 is still under construction, modeling and simulation (M&S) tools were used to develop tactics, techniques, and procedures (TTPs) to employ the aircraft. Our overall goal was to utilize a fleet of Airlander 10s to minimize the reliance on surface ships in the Arctic for surface surveillance and control (SSC) missions. To achieve this end state, we used immersive synthetic environments (ISE) to determine if the

Airlander could launch and recover unmanned aerial systems (UAS) over the Arctic to conduct SSC.
Our CRUSER project final report details how the ISE was developed, how concept of operations (CONOPS) were modeled in the virtual environment, and how simulations were used to determine the optimal force mix required based on the size of the surveillance area. The current landscape of the Arctic was surveyed, including the existing base infrastructure and potential support for Airlander 10 operations. In addition, the geopolitical environment of the Arctic and the existence of a governance structure for operating unmanned systems (both in airspace and the maritime environment) were investigated to determine legal implications for operating UASs from the Airlander over the Arctic.

Accomplishments:

- We developed two ISEs to support evaluation of the operational environment in the Arctic. This allowed for detailed mission planning which revealed specific capability gaps that need to be addressed in future work.

Figure 9: Platform view under Airlander 10 as ScanEagle is recovered. Source: NPS

    - The first ISE developed was a constructive simulation showing SSC operations from both Thule Space Force Base (SFB) and Eielson Air Force Base (AFB), which demonstrated the feasibility of intelligence, surveillance, and reconnaissance (ISR) missions using the ScanEagle deployed from the Airlander 10.
    - The second ISE developed was an immersive environment viewable in the Meta Quest Pro virtual reality (VR) head-mounted display (HMD). The environment allowed the user to virtually stand on the platform of the Airlander 10 as shown in the figure during ScanEagle launch and recovery operations.
- The legal research found significant gaps in governance for UxS in the Arctic region. The legal researchers offered the following three key recommendations:
    - Create a U.S. interagency working group to assess the use of UxS in the Artic by federal agencies in order to develop policies for U.S. use and, eventually, international coordination.

- Task a working group within the Arctic Council to examine current and future uses of UxS in the region and the establishment of monitoring and enforcement mechanisms.
- Fill in the gap in international policy regarding UxS using the findings of the U.S. study and Arctic Council Working Group.

Education:

- Rebecca Grippo, external student from Roger Williams University School of Law, was supported as a summer intern. She gave a briefing in July 2022 and her report is posted at: https://nps.edu/documents/114698888/131233620/EAG-CRUSER+Report_Arctic+Governance+%28Aug+2022%29.pdf/5c9d63e1-7739-3daa-4c2b-e134d2d7f679?t=1666134799193
- Captain Tim Socha is currently working on his thesis investigating Airlander 10 operations in the Arctic. His planned graduation and thesis submittal date is March 2023.

Dissemination:

- The legal analysis and recommendations will be shared as an independent report with Navy attorneys who work on UxS legal issues.
- NPS has purchased 4 Meta Quest Pro HMDs which will be provided to HAV to support their messaging on the operational capabilities of the Airlander 10. Specifically, these HMDs will be used to show their Ministry of Defense (MoD) the unmanned aerial vehicle (UAV) launch and recovery operations.

Collaboration and Partnership:

- NPS currently has a CRADA with HAV that is going to allow our researchers to continue investigating military use-cases for the Airlander 10.
- The legal research team worked closely with the U.S. Coast Guard and NOAA to understand federal use of UxS in the region. Findings will be disseminated to these agencies to advance the creation of relevant policy and governance.

Transition:

The research sought to determine the utility of ISEs in ideating new ideas and concepts to assist the Department of Defense (DoD) and MoD's acquisition community. Through this process, the researchers worked closely with HAV to determine the specific features that are needed to best support military customer requirements. This research has also developed recommendations to address a gaps in governance and policies identified for these systems operating in the Arctic region. All of these findings will help HAV as they interact with the acquisition community as they have dedicated research to support their proposed operational use-cases.

Future work includes investigating crew resource management and crew rest to support Airlander 10's five (5) loiter time.

F. ADVANCING CLARITY: ANALYSIS OF UXS LEGAL QUESTIONS

Participants

- Principal Investigator (PI): Kristen Fletcher / kristen.fletcher@nps.edu
- Co-PIs: Eric Hahn / ehahn1@nps.edu Marina Lesse / marina.lesse@nps.edu
- Students:

Rebecca Grippo, Law, Roger Williams University School of Law
Philip DeCocco, Political Science, Marquette University

Major Goals

The project objectives were to advance legal clarity of U.S. operation of unmanned systems (UxS) around the globe through analysis of legal questions posed by Navy attorneys that arise often in UxS operations. The team expanded research into two key areas: (1) application of U.S. environmental law to expandable or disposable UxS and (2) legal questions that arise in the classified setting. Research included national and international laws that apply to these systems, legal and policy gaps that can hinder use by the U.S. or allies, and understanding of the impacts of systems that are deemed expendable or disposable. Two underlying goals were to ensure that DoD and the Services lawfully operate UxS and to contribute to the body of law and policy research relevant to expendable systems.

Researchers focused on law and policy research to build on the body of literature that has identified early legal and policy gaps. Researchers collaborated with public and private sector partners to ensure that the subtleties and unanswered questions in US, allied states, and international laws were considered. Given the uncertainties embedded in the questions, especially around expendable systems, developing a network of individuals and agencies using these systems was essential. In addition, researchers analyzed caselaw, statutes, treaties and official policies, such as DoD and Navy directives and instructions.

Accomplishments:

- Advancing Legal Clarity Report – The primary outcome is a report detailing the legal analysis of key UxS questions and statutory treatment of expendable systems. The report lays out 2 scenarios that detail laws that apply to expendable systems as they operate in different maritime zones including international waters, EEZs and overlapping jurisdictions U.S. waters. A briefing of the Advancing Legal Clarity Report will be offered to a CRUSER meeting in 2023.
- Appendix: A report appendix will be created in the classified environment to that puts the research into a classified context.
- Key findings include:
    - There is currently no governance structure to address the increasing use of expendable systems. Each year, many thousands of systems are left behind, in a water environment or on land, and over time, release toxic substances into the environment and can create navigational hazards.

    - Researchers recommend the DON work with other agencies reliant on expendable UxS to establish mechanisms to reduce the impact of these systems, including in the design phase.
    - To address the open legal questions posed by Navy attorneys, researchers provide indepth analysis and possible outcomes to challenges but conclude that there are no clear answers as the law is still evolving in this area.
- A final key outcome is the expansion of collaboration in year 2 of research on UxS law and policy. Legal and policy questions arise in a variety of contexts from design, operation, and partnership of UxS with people or other systems and the increasing number of colleagues interested in these issues enhanced the analysis and findings.

Education:

- Capstone Project under the Human-Autonomy Teaming Project is underway. Legal research has directly contributed to the team's design work and planned operations.
- Summer interns conducted research on legal treatment of UxS in different maritime zones, air space, and specific regions, along with the impacts of expendable/disposable UxS.

Dissemination:

Fletcher, Lesse, Briefing, CRUSER Monthly Meeting (May 2022)

Grippo, DeCocco, Intern Briefing, Energy Academic Group (July 2022)

DeCocco, Report, *Treatment of Expendable Systems Under U.S. Environmental Law* (August 2022)

Grippo, Report, *Arctic Governance over Autonomous Systems in the Arctic* (August 2022)

Lesse, DeCocco, Fletcher, *Advancing Clarity: Analysis of UxS Legal Questions*, OCEANS 2022, Hampton Roads (2022).

Lesse, Presenter, OCEANS 2022 (October 2022)

Fletcher, Planning Team Member, Moderator, AI and Climate Change (AAAI Symposium) (November
2021)

PI Fletcher and Co-PI Lesse have a paper underway on environmental implications of expendable autonomous systems, with DeCocco as a co-author.

Collaboration and Partnership:

University of Alabama Huntsville – Through the CRUSER-funded Human-Autonomy Teaming project, legal research has been shared with faculty and students at the University of Alabama Huntsville and public and private sector partners including Boeing, NASA and Dynetics.

The Technical Cooperation Program (TTCP) – Through the Artificial Intelligence Strategic Challenge, PI Fletcher and Lesse have participated in the Law and Ethics Theme Team with colleagues from the UK, Canada, Australia and New Zealand. This work was funded in part by OUSD(R&E).

U.S. Coast Guard – Fletcher and Lesse contributed information on environmental impacts of expendable systems to colleagues at the 2022 EVERGREEN event (August 2022).

Transition:

- CRUSER 2023 Project: Fletcher and Lesse are awaiting results of submitted proposal on The Role of Unmanned Systems in Meeting Climate Challenges.
- Two invited white papers are under consideration by NASA for analysis of legal gaps related to autonomous systems and how to design a system in the absence of legal clarity.
- NRP: Fletcher and Lesse are also part of an NRP-funded project for FY23 that addresses the role of unmanned systems in the future force structure and whether they may contribute to reaching net zero emissions for the operational Navy. Results of this work will be presented to ONR for future climate-related funding.

G. UXS MANNED/UNMANNED SECURE TEAMING

Participants

- Principal Investigator (PI): Dr. Britta Hale <britta.hale@nps.edu>
- Co-PIs: Dr. Douglas Van Bossuyt
- Supporting Researchers and other supporting faculty: Aurelio Monarrez, Joseph Lukefahr, Jonathan Lussier, and Christopher Manuel
- Students:
    - LT Andre Leon
    - LT Christopher Britt

Major Goals

Modern unmanned systems (UxS) rely upon secure data links to provide command and control links in limited and contested environments and especially against threats posted by cyberattacks. The most common currently fielded security framework applied to UxS command and control links relies heavily on *synchronicity* of connections, leaving command and control links prone to high-latency and persistent session establishment issues and even operational failure. In addition to this, all data under the entire channel key lifetime is trivially lost in the event of a cyberattack, leaving UxS operators at risk from their own devices for time windows of days or even weeks. A new protocol known as the Messaging Layer Security (MLS) [5] protocol is under standardization by the Internet Engineering Task Force (IETF) that not only offers asynchronicity but also allows self-healing from a cyberattack under certain conditions. It furthermore is a multi-device security protocol that optimizes for efficiency. This work looks at testing MLS for UxS, providing a simulation and hands-on test to evaluate viability of MLS supporting UxS groups.

Accomplishments:

- We integrate and test MLS on the Robotic Operating System (ROS).
- We perform a virtual environment simulation test of MLS in ROS.
- We test the MLS implantation physically on the ScanEagle Unmanned Aerial Vehicle (UAV) and Naval Information Warfare Pacific CASSMIR Unmanned Surface Vehicle (USV).
- We demonstrate the use of MLS for secure and efficient C2 and exchange of data between the UAV and USV in the multi-domain ad-hoc network configuration. The experiments included both in a virtual environment and on the physical UxS that shows that MLS has the potential to securely and efficiently C2 with distributed UxS forces.
- We conclude that MLS has strong potential for improved security and synchronicity support for security of command and control of UxS.
- Furthermore, we demonstrated the work to partner forces (the Norwegian Defense Research - FFI) and various NATO members.
- As a result of that effort, further collaboration with FFI and Kongsberg Aerospace and Defense has been initiated to expand on testing MLS for UxS and defense use cases.

Education:

- Andre Leon and Christopher Britt. *UxS Cryptologic Protocol Requirements for Multidomain Operation and Joint Interoperability*. Naval Postgraduate School. Master's Thesis. June 2022. http://hdl.handle.net/10945/70738
- Seminar for NPS Computer Science and Information Science students on UxS security

Dissemination:

- C. Britt, A. Leon, B. Hale. C2 Superiority in an Era of Technological Competition. In Proceedings of Signal, AFCEA 2022.
- C. Britt, A. Leon, B. Hale. Asynchronous C2 and Multi-Device Capabilities in DON Networks. In Proceedings of CHIPS: Department of the Navy Information Technology Magazine. Jan-Mar issue, 2022.
- Two peer-reviewed articles in draft
- Presentations:
    - NavalX
    - Unmanned Vehicle and Autonomous Systems (UVAS)
    - Unmanned Task Force
- Outreach and briefs on research effort:
    - Naval Cyber Warfare Development Group (NCWDG)
    - NIWC-PAC
    - NAVSEA Corona
    - ONR
    - NAVAIR
    - WARCOM
    - PMW 120
    - PMW150
    - PWM160

Collaboration and Partnership:

A CRADA was built with ExScientia for collaboration on project, including implementation for the simulation. NIWC-PAC collaborated on testing on the NIWC-PAC CASSMIR unmanned surface vessels. FFI hosted a visit to demo the simulation portion of the test for FFI and NATO members.

Transition:

Outreach and engagement have been made to PMW120, PMW150, PMW160, NCWDG and ONR. Both ONR and NCWDG expressed concrete interest, with ONR funding a preliminary supplemental effort for qualitatively evaluation of DoD UxS stakeholder protocol requirements through an IRB interview study. NCWDG expressed firm interest in longer term funding, starting in 2024 or 2025 (due to the timeline to secure approvals).

H. BION - BEHAVIOR INTEGRATION AND OPTIMIZATION FOR NETWORKED CONTROL SYSTEMS (NCS)

Participants

- Principal Investigator (PI):
  - Douglas Horner, Undersea Warfare, dphorner@nps.edu
- Co-PIs:
  - Dr. Ruriko Yoshida, Operations Research, ryoshida@nps.edu
  - Dr. Geoffrey Xie, Computer Science, xie@nps.edu
- Students:
  - LCDR Andrew Faulk, USN
  - LT Antony Murururi, USN
  - ENS Dan Harter, USN
  - CPT Fritz-Schreck, USA

Major Goals

After discussions with several naval warfare communities, a consistent consensus emerges when talking about the future of unmanned system integration with naval forces. It principally revolves around three design principles: 1. The need to retain flexible, human control of the system. 2. A design, from the ground up, that emphasizes collaborative, multi-vehicle operations. 3. A flexible autonomy architecture design to handle a diverse set of mission requirements.

There is a significant gap in the Navy's current development of autonomy architectures. It doesn't adequately handle the above criteria and it isn't designed to ``scale up''. By this we refer to the ability to rapidly integrate different functionality (or behaviors). System behaviors should be able to rapidly integrate into an autonomy architecture. Our goal is to ``commoditize'' the behavior development process. The behaviors should be developed by anyone where the interfaces and functionality permit interoperability and composability. By doing this we hope to provide a framework for rapidly improving system autonomy while addressing current ``scaling up'' autonomy limitations common with many proprietary solutions. Our underlying hypothesis is that a framework for construction and integration of software-defined behaviors is a critical component for developing greater system autonomy.

Accomplishments:

- BION integration with Modeling and Simulation Toolbox (MAST) using ROS2 as a communications interface. Integration with the Naval Surface Warfare Center Dahlgren, agent-based simulation MAST permits an important tool for evaluating the value of unmanned network control systems for naval and expeditionary scenarios.
- Redesign of the MATLAB architecture to support greater UxV NCS flexibility and world-wide scenario development.
- Development of C++/ROS2 software control architecture in preparation for conducting UxV NCS experimentation at Camp Roberts, CA.
- Development of MAST mission scenarios for Surigao Straits (Surface Warfare) and San Clemente Island (Naval Special Warfare) for testing.

- Conducted background research and selected an approach for behavior development and integration for unmanned networked control systems.

Education:

- LCDR Andrew Faulk, USN & LT Antony Murirori, “Increasing Utility and Fidelity of A UxV Networked Control System Simulation via Python Adaptation,” Master of Science, thesis, Dept. Comp Sci.

Dissemination:

- R. Yoshida, C. Vogiatzis and K. Marler, "Routing Against Uncertainty: U.S. Marine Corps Rapid Planning and Logistics Routing Against Uncertainty". To appear in Naval Engineers Journal.
- Y. Liu, C. Vogiatzis, and E. Morman, "Solving reward-collecting problems with UAVs: a comparison of online optimization and Q-learning. Journal of Intelligent & Robotic Systems. DOI 10.1007/s10846-021-01548-2

Collaboration and Partnership:

- NPS SEED Center – Assisted with MAST simulation and helped to develop agent- based mission scenarios.
- NSWC Dahlgren – Assisted with developing a messaging interface to MAST.

Transition:

This program has been successful in transitioning to a 3-year research program funded by the Assistant Secretary of the Navy for Operational Energy. The name of the research program is Opportunities for Long Dwell Group UASII/III UxVs to Improve Raid Annihilation Capabilities of Current Surface Capabilities. The goal is two-fold: First to develop a simulation for evaluating the utility of a UxV NCS from an Operational Energy perspective. Second, to demonstrate the UxV NCS BION control system from an FFG with fixed wing UAVs and surface USVs.

I. AQUA-QUAD SENSOR INTEGRATION AND PARTICIPATION IN TRIDENT WARRIOR 2022

Participants

- Principal Investigator (PI): Kevin Jones <kdjones@nps.edu>
- Co-PIs: Vladimir Dobrokhodov, Paul Leary, Kevin Smith
- NUWC Keyport Collaborators: Mark Paulus, Daniel Gentile, James Richards, Shawn Stainsby
- Students:
    - CAPT Christian Thiessen: CUAS payload design and experimental test flights.
    - LT Zachary Ceroli: Numerical simulation of multi-copter configurations.
    - Tristan Williams: CSUMB summer intern.
    - DA3304: Prototyping test case.

Major Goals

The primary goals this year included:

- Continue the development and testing of the novel acoustic sensor payload with the team at NUWC Keyport, with the goal of participation in Trident Warrior 2022 or other high-profile events.
- Explore sea-state sensitivity for launch and recovery of Aqua-Quad.
- Explore development of an NPS version of the payload.
- Evaluate aerodynamic effects of the solar array, and approaches to alleviate negative impacts on cruise performance.

Accomplishments:

While much was accomplished this year, a reduced budget and personnel changes in the NUWC Keyport team introduced challenges ultimately preventing participation in TW22. Collaborative efforts with Keyport were reduced to developments to address heat management issues with the payload and a single week of range testing. During that experiment, personnel shifted back, and if budgeting issues can be resolved, the payload appears to be on the verge of a full system demonstration. Accomplishments realized this year included:

- Good acoustic tracking data produced from the NUWC Keyport payload mounted in Aqua-Quad.
- Payload heat-management resolved through the use of a heat-sink integrated into the pressure vessel at the waterline, and more efficient use of compute resources in the payload.
- Flight testing in breaking waves, demonstrating the ability of Aqua-Quad to survive tumbling, and the ability to arm the motors and get airborne while riding a wave as it was breaking.
- Evaluation of the aerodynamic impacts of the solar array in cruise flight. Results from theory and flight tests demonstrate a coupling between maximum flight speed and total vehicle weight, with higher flight speeds possible for higher total weight.
- With the aid of a CSUMB summer intern, experiments were initiated for a modified configuration using horizontal thrust motors, allowing the Aqua-Quad to remain

relatively level at higher cruise speeds. Theory suggests that cruise speeds could be nearly doubled for the same power currently required.
- Integration and testing of a counter UAS payload with CAPT Christian Thiessen (CS), with flight demonstrations at the Monterey Bay Academy COA and at Camp Roberts.

Education:
- Thiessen, C. M., "Redesigning the Counter Unmanned Systems Architecture," Masters thesis, Naval Postgraduate School, 2022.
- Ceroli, Z., "Computational Multicopter Modeling and Design," Masters thesis, Naval Postgraduate School, 2022.
- Tristan Williams, CSUMB summer intern project.
- Prototyping case study in DA3304.
- Initiating collaboration with USNA, CAPT Brad Baker, for education in AM for lightweight, watertight structures.

Dissemination:
Details of the design and results of the NUWC Keyport payload are sensitive and are not currently suitable for release in open literature. However, a new provisional patent application was filed by Keyport TPO 3 weeks ago including both teams. The other new accomplishments have not yet been published. A number of previous publications and theses have documented early achievements with Aqua-Quad, along with two patents, an article in the Monterey Coast Weekly.

Collaboration and Partnership:
- Naval Undersea Warfare Center, Keyport Division: Mark Paulus, Daniel Gentile, James Richards, and Shawn Stainsby.
- USSOCOM NSW-G8: Paul Davis, Kevin Callaway and others.
- NPS: Britta Hale and Douglas Van Bossuyt.
- Initiating a CRADA with Formlabs to investigate the use of SLS printing for stronger, lighter and more watertight airframe components.
- Initiating collaboration with USNA, CAPT Brad Baker, for education in AM for lightweight, watertight structures.

Transition:
We had hoped to transfer several complete systems to NUWC Keyport, but they are still working on the necessary approvals (Lithium, flight-operations, etc.). We have transferred partial systems to them for non-flight testing of the payload. We had hoped to have the payload integration at a state where we could begin work with outside vendors to produce small numbers of systems for broader testing in the fleet, but unfortunately the payload in not yet at a state where that is feasible. We have started to pursue additional payloads, in an attempt to push Aqua-Quad into other markets.

J. PERSISTENT SMART ACOUSTIC PROFILER (PSAP)

Participants

- Principal Investigator (PI): John Joseph, email: jejoseph@nps.edu
- Co-PIs: Yi Chao (Seatrec Inc) and John Ryan (MBARI)
- Period of Performance: 01 Jan – 31-Dec 2022
- Students: LCDR Casey Burgener, METOC Curriculum (373)

Major Goals

This project fully embraces the notions of the Naval Intelligent Autonomous Systems (IAS) Strategy through development of a novel autonomous profiling system that can provide the warfighter with persistent, real-time acoustic characterization of the undersea battlespace. This autonomous system, designated here as the Persistent Smart Acoustic Profiler (PSAP), is designed to provide sustained support over extensive operational periods by furnishing unlimited system power through an ingenious energy-harvesting process that extracts energy directly from ocean thermal gradients through solid-to-liquid phase transition. The profiler also employs smart hydrophone technology that distills raw acoustic data into short information messages that can be readily transmitted to a distant command center (land or sea based). Two-way communication allows remote operators to adjust mission parameters as needed based on changes in mission needs and/or environmental conditions. Figure 1 provides an overview of the PSAP concept of operations. PSAPs can be used as independent units or combined into a network providing wide-area coverage of the maritime battlespace. These systems enable an innovative concept of operations that can support a broad spectrum of naval undersea warfare (USW), intelligence surveillance and reconnaissance (ISR) and battlespace awareness (BA) missions.

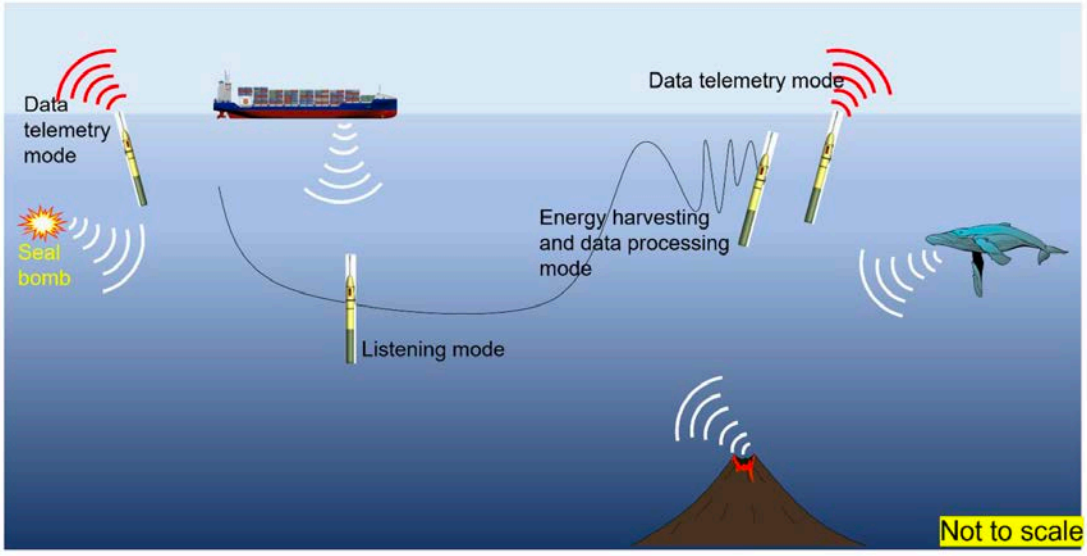

Figure 10: PSAP concept of operations combine a unique energy-harvesting buoyancy engine (Seatrec) and smart hydrophone technology (Ocean Sonics) to provide the warfighter with persistent maritime surveillance.

Accomplishments:

The contract for the procurement of the profiler platform was not awarded until late-September due to the late arrival of CRUSER funds at NPS and an extensive contracted purchasing process. Since that time, the project co-PI's have met with Ocean Sonics, maker of the icListen RB9 Smart hydrophone, to begin integration of the hydrophone on the profiler platform to minimize interference with system noise and acoustic reception. Once integration of the hydrophone is completed, the system will be field tested for performance in several areas. Comparisons to data collected at the MBARI MARS Cabled Observatory, which uses the same RB9 Smart hydrophone, will be made to evaluate acoustic performance and develop signal processing algorithms. Data from this field work will be the basis of student thesis research. To optimize the PSAP system for real-world research and operational applications, students will measure and document the performance of the three fundamental functions of the system in various environments: (1) passive acoustic listening performance, (2) energy harvesting performance and (3) on board data processing and communications capability. It is anticipated that performance improvements and expanded capabilities will be addressed in future research efforts using the PSAP platform.

Education:

- PSAP offers numerous opportunities for student thesis research. In addition to evaluating and optimizing the three fundamental functions described above, student research efforts can focus on expanded capability such as using multiple PSAPs to work as a sparse array for wide-area surveillance, improve its library of detection algorithms, add steering capability by using predicted currents, add additional sensors that can improve USW-related capability, investigate energy efficiencies that support integration of additional sensors while minimize energy-harvesting demand.
- In addition to supporting student research, PSAP can be used in support of applied courses in oceanography such as Tactical Oceanography and Descriptive Oceanography as well as courses in robotics that address remote piloting and controls of undersea autonomous vehicles. PSAP data can be applied in courses that teach development of auto-detection methods, including applications of AI/ML methods to characterize signals of interest.

Dissemination:

Because of the late award of the PSAP contract with Seatrec, results from this project are not ready to publish in peer-reviewed publications. As student thesis efforts document and expand the performance of PSAP, thesis will be published and peer-reviewed papers on applications in underwater acoustics, soundscape analysis and battlespace awareness, are anticipated. A public announcement of the Seatrec/NPS partnership in this project has been disseminated simultaneously by NPS PAO and Seatrec.
A presentation on the project was made at the August CRUSER Monthly Meeting.

Collaboration and Partnership:

The concept for this project developed from conversations with Dr Yi Chao following a seminar he presented at NPS in July 2021. Dr Chao is a renown physical oceanographer and ocean modeler, formerly at NASA's JPL and now CEO (and founder) of Seatrec Inc,

a spinoff from CalTech to commercialize the patented energy-harvesting technology. During his visit to Monterey, Dr Chao also met with Dr John Ryan, a research scientist at MBARI who NPS has collaborated with in various projects on soundscape characterization and use of passive acoustic data in marine mammal ecology research. Recognizing the potential that development of a long-endurance autonomous ocean/acoustic sensing platform can contribute to soundscape monitoring, marine mammal ecology and numerous naval applications, the three of us submitted a joint proposal to the CRUSER SEED Call for Proposals that was well-aligned with the DoN IAS Strategy.

Transition:
This effort has many applications to both civilian and naval research and operations. The unique energy-harvesting technology enables PSAP to overcome power limitations suffered by most small underwater autonomous systems, resulting in unprecedented endurance performance. As the system is matured and performance documented through field testing supporting student research, we intend to further demonstrate and advance system capability with additional support. At the appropriate time, we will socialize PSAP with potential sponsors at ONR, N45-LMR, UWDC and NOAA.

K. COLLABORATIVE HYPER-ENABLED OPERATIONS IN CONTESTED ENVIRONMENTS (CHOICE)

Participants

- Principal Investigator (PI): Isaac Kaminer, kaminer@nps.edu
- Co-PIs: Aurelio Monarrez
- Students:
    - LTJG Christopher Mears, Thesis Student, Curriculums 697 and 366
    - LT Jiles Maness, Thesis Student, Curriculum 697
    - LT Austin Dumas, Thesis Student, Curriculum 5270
    - LCDR Hans Lauzen, Thesis Student, Curriculum 5270

Major Goals

The overall objective is to develop a collaborative mapping framework using teams of unmanned aerial vehicles (Insitu Scan Eagles and Teal Golden Eagles) and unmanned surface vehicles (USV), with communication capabilities that include Starlink, all operating in a complex, GPS-denied, littoral environment. This unmanned vehicle (UxV) system will build, maintain, and deliver digital maps of potential landing zones for exploitation by human forces waiting offshore. We plan to demonstrate these technologies in a realistic littoral environment with beach/rock/marsh shorelines, multiple inlets, and near-shore obstacles including rocks, aquatic vegetation, trees, or man-made structures.

Accomplishments

- Developed software that remote tasked Teal Golden Eagle UAS via Stralink
- Developed software that controlled 3 Teal Golden Eagles via one Ground Control Station
- Developed software that remote tasked 3 Teal Golden Eagles via Starlink
- Developed software that remote tasked Insitu ScanEagle UAS via starlink

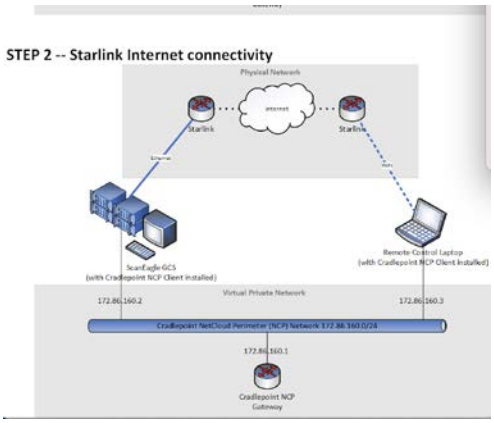

Figure 11: Starlink Internet Connectivity

Education

- C. T. Mears and J. G. Maness, “Hyper-enabling operators with unmanned systems and pLEO constellations,” Master’s thesis, Dept. of Defense Analysis (with Space Systems Operations), Naval Postgraduate School, Monterey, CA, 2023.

- LT Austin Dumas, NSW student in Space Systems Operations/Engineering (dual major) and LCDR Hans Lauzen, Information Officer in Space Systems Operations will build upon this CRUSER research for their theses.

Dissemination

- Cichella, V.; Kaminer, I.; Walton, C.; Hovakimyan, N.; Pascoal, A. Consistency of Approximation of Bernstein Polynomial-Based Direct Methods for Optimal Control. Machines 2022, 10, 1132. https://doi.org/10.3390/machines10121132

Collaboration and Partnership

Naval Special Warfare Special Reconnaissance Team 1 contributed to the flight testing. They were the Aerial Vehicle Operators for ScanEagle and Golden Eagles. Collaborated with Red Cat (Teal) through a Cooperative Research and Development Agreement. The collaboration enabled student engagement with Red Cat engineers to develop a VPN onboard Golden Eagle Ground Control Station. The development of the VPN allowed for remote tasking of vehicles. In addition, further development permitted the controlling of 3 vehicles from one ground control station.

In addition, we have been discussing a joint NPS/MIT/Insitu experiment to be held in Camp Roberts in the Fall of 2023.

Transition

Engaged with Naval Special Warfare Command and they have expressed interest in continued funding of this type of research due to the alignment with their AI for Maritime Maneuvering future concept.

We have submitted a completed MIT/NPS proposal to ONR.

L. PROOF-OF-CONCEPT: ACHIEVING FREE PROPULSION FOR FLEXIBLE UUVS USING VORTICAL WAKES

Participants:

- Principal Investigator (PI): Joseph T. Klamo, SE Dept. <jklamo@nps.edu>
- Co-PIs: Jarema M. Didoszak, MAE Dept., Young W. Kwon, MAE Dept.
- Students: LT Devon L. Florendo USN, 580 curricula

Major Goals:

The objective of this effort was to experimentally demonstrate that propulsion from a passive, but flexible, synthetic body with a rectangular cross-section is possible by having the body synchronize with an incoming vortical flow. Previously, a research group at the Massachusetts Institute of Technology (MIT) demonstrated this concept using an actual fish that had been euthanized. This investigation used a fabricated synthetic flexible body that had a more traditional underwater vehicle cross-sectional profile.

Our approach involved having a Systems Engineering graduate student fabricate numerous synthetic flexible bodies and then experimentally test them as part of his Master's thesis research. The flexible synthetic bodies were created using silicone rubber that was poured into a mold to create the desired body shape. The mold was created using additive manufacturing techniques and rapid prototyping technology that exists at the Naval Postgraduate School (NPS). The flexible body was then experimentally tested in a recirculating water tunnel at NPS. A testing fixture was used that held the flexible bod and allowed for the measurement of the drag and side force on the body using a load cell. A D-shaped cylinder in front of the flexible body produced the vortical wake that interacted with the flexible body. The figure below is two photos of the test set-up showing the synthetic body held in the test section of the water tunnel.

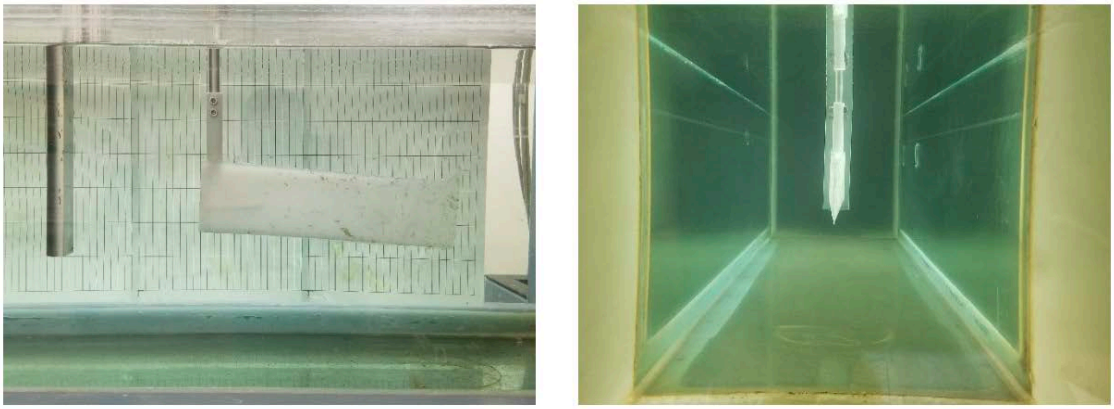

Figure 12: Side view of the test set-up showing the D-shaped cylinder and flexible body (L) and view from behind the body looking forward inside the test section (R).

Accomplishments:

- Designed and 3d printed a mold for creating flexible bodies and an adapter for holding a body in the test section during testing;
- Fabricated a rectangular cross-section synthetic flexible body using silicone rubber with a mounting adapter embedded in the body;

- Designed and built a testing fixturing for supporting a D-shaped cylinder to create a vortical wake and securing the flexible body and adapter to a load cell to measure the forces on the body;
- Tested the synthetic flexible body in a recirculating water tunnel over a range of incoming flow speeds and measured the time history of drag and side forces on the body.

Education:
D. L. Florendo, "Using Design-Test-Build Cycles to Demonstrate Free UUV Propulsion in a Karman Vortex Street Using a Flexible Body," Master's thesis, Systems Eng. Dept., Naval Postgraduate School, Monterey, CA, USA, ***expected June 2023***.

Dissemination:
This is the first year of this SEED-funded research effort with testing still on-going and therefore we have not disseminated any of our results yet. We plan to publish the testing results in a future journal article.

Collaboration and Partnership:
This research effort involved internal NPS collaboration between SE and MAE departments.

Transition:
A proposal entitled "CAREER: Achieving Free Propulsion Through Passive Synchronization With a Vortical Flow by Custom Designing Flexible Bodies" was submitted to the National Science Foundation (NSF) fluid dynamics program for consideration in 2022. It proposed to continue this research effort by looking at the possibility of achieving passive synchronization of multiple in-line bodies along with floating bodies. Unfortunately, this proposal was declined by NSF. We plan to submit an updated version of that proposal to the Office of Naval Research (ONR) Advanced Naval Platforms Division, code 331 in 2023.

M. SURFACE: SWARMING USVS AND RESILIENT FORMATIONS AGAINST CONTESTED ENVIRONMENTS

Participants

- Principal Investigator (PI): Sean Kragelund, spkragel@nps.edu
- Co-PIs:
  - Isaac Kaminer, kaminer@nps.edu
  - Matt Feemster, feemster@usna.edu, U.S. Naval Academy
  - CDR Paul Frontera, frontera@usna.edu, U.S. Naval Academy
  - Violet Mwaffo, mwaffo@usna.edu, U.S. Naval Academy
- Students:
  - LT Matt Heubach, Thesis Student, Curriculum 5274
  - LT Keegan Delanoy, Thesis Student, Curriculum 5275
  - ENS Jennifer Nguyen, Thesis Student, Curriculum 5274
  - Other ME4811 Students in Curriculum 5274: LT Timothy Howarth, Kia Min Phua

Major Goals

SURFACE represented a new research collaboration between NPS and USNA in two related areas. NPS researchers focused on the development, simulation, and field testing of hybrid attack trajectories for a USV swarm, culminating in an ONR force-on-force field experiment. This project implemented optimal trajectory generation and coordinated path following algorithms to produce "aggressive" trajectories for a fleet of USVs. This effort leveraged information technology (IT) automation solutions to produce a software development and deployment framework for rapidly fielding new capabilities in the austere environments. Other research objectives investigated techniques for enabling these capabilities in contested environments.

USNA researchers investigated a graph rigidity formation control (RFC) approach for positioning a group of USVs in navy-relevant applications like high value unit escort. The primary objectives of this work were: i) development of a pathway for implementing this RFC scheme on marine platforms, ii) experimental evaluation of the RFC algorithm for comparison to alternative formation strategies, iii) analysis for subsequent performance improvements, and iv) improved vessel dynamics models (to include environmental disturbances) via in-situ data collection. Another goal of this project was to foster an active collaboration between aligned faculty/students at NPS and USNA for research exchange, student continuity, and shared utilization of vehicles, hardware, and software.

Accomplishments:

NPS

- Developed Robot Operating System (ROS) software modules for optimal trajectory generation, nonlinear path following, and inter-vehicle coordination. Algorithms were successfully demonstrated on Lake Del Monte using NSWC-Carderock "Sandwich Boats."
- Developed a portable architecture for running all NPS backseat driver software as a Docker container on any USV computer. This architecture also utilized Ansible

to rapidly configure, compile, and deploy software updates to all USVs on the swarm network.
- Successfully integrated and tested NPS software developed for low-cost "Sandwich Boats" onto NSWC-Carderock's larger, faster, jet-powered USVs during a two-week field experiment.
- During field experimentation, NPS faculty and students developed innovative USV employment and intervention tactics to maximize their effectiveness within applicable swarm control frameworks.
- NSWC-Carderock decided to adopt a ROS/Docker/Ansible architecture proposed by NPS for their USV swarm projects going forward.
- Collaborated with NSWC-Dahlgren to connect NPS software into a virtual simulation environment based on the Arma 3 video game, which will facilitate testing of vision-based perception algorithms in contested environments.

USNA

- Experimentally implemented Rigid Formation Control (RFC) on three Kingfisher USVs in College Creek.
- The RFC algorithm was augmented with a minimum steerage low-level controller to allow the vehicles to always operate in the forward direction.
- Deployed code via Ansible which aligns with NPS deployment.
- Initiated conversion of USNA Kingfisher to accept NPS formation commands via ROS.
- A grey-box modeling method leveraging maximum likelihood estimation was proposed to calibrate a linear model of USV operating in marine environments with stochastic noise capturing water waves, wind gusts, and other unmodeled dynamics.
- A transfer learning procedure to train a Deep Neural Network (DNN) to detect objects of interest in raw video images using a Depth AI Camera sensor was initiated and preliminary work conducted to incorporate a single or multiple sensors on USV.

Education:

- J. Heubach, "Use of artificial fiducial markers for USV swarm coordination," Master's thesis, Dept. of Mech. and Aero. Eng., Naval Postgraduate School, Monterey, CA, 2022.
- K. Delanoy, "Swarm tactics using aggressive trajectory generation and optimal path planning with USVs," Master's thesis, Dept. of Mech. and Aero. Eng., Naval Postgraduate School, Monterey, CA, 2023 (in progress).
- NPS course ME4811 Multivariable Control of Systems: students learned about cooperative path following, filtering noisy sensor data, and conducted hands-on system identification experiments to develop a speed controller for the low-cost "Sandwich Boats."
- NPS course ME4823 Cooperative Control of Multiple Autonomous Vehicles: students learned about swarm control algorithms and developed simulated tactics using ROS and the Gazebo simulation environment.

- ENS Jennifer Nguyen completed a USV capstone project with Matt Feemster as a MDN at USNA and is now working on a related thesis project with Sean Kragelund as a Bowman Scholar at NPS. ENS Nguyen is working on vision-based perception algorithms for USVs.
- USNA course EW413 Digital Control Systems: midshipmen were tasked with the design and integration of a low-level turn rate control algorithm for the Kingfisher vessel. Turn rate control is needed to properly interface with NPS formation control algorithms.
- USNA course EW453 Computer Vision: midshipmen were trained to annotate raw picture frames, train a DNN using Google Colab, and deploy their model on the OAK-D Depth AI Camera

Dissemination:

- P. Frontera, M. Feemster, and J. Nguyen, "Application of Rigid Formation Control to Marine Vessels," submitted to *Ocean Engineering*, September 2022, in review.
- V. Mwaffo, P. Frontera, M. Feemster, and S. Kragelund, "Maximum Likelihood Identification of the Uncertain Dynamics of Unmanned Surface Vehicles", submitted to the 2023 American Control Conference

Collaboration and Partnership:

NPS has become a value-added member of ONR Code 34's research portfolio. In this role, NPS has collaborated closely with NSWC-Carderock and NSWC-Dahlgren as described above. **However, at the sponsor's request, NPS has agreed only to disseminate details of this work to DoD and U.S. DoD contractors (DISTRIBUTION D).**

Academically, SURFACE has established a new research collaboration between NPS and USNA.

Transition:

NPS obtained matching funds from ONR in 2022, and ONR agreed to more than double this funding level in FY23. Subject to NPS continuing its strong performance in 2023, ONR intends to transition this research to full ONR funding in 2024.

N. HUMAN-AUTONOMY TEAMING: CONTROL OF MULTI-DOMAIN UXV'S

Participants

- Principal Investigator (PI): Mollie McGuire <mrmcguir@nps.edu>
- Co-PIs: Aurelio Monarrez

Major Goals

The objective of the research was to examine the capability of operator's ability to manage multiple UxVs in a multi-domain environment. The first half of this project was to interface with different commands with interest and investment in UxSs to understand the use and need in the future of managing multiple UxSs. In addition to having SME input in scenario development, so that the simulation reflected realistic scenarios, and the task management was appropriate for the mission. Building on this, the second phase was to then conduct experimentation with operators managing UAVs and UUVs at the same time for a specific mission, using a common ground control station.

Accomplishments:

- Meetings with multiple organizations and SMEs in scenario development and design considerations for the next line of experimentation.
- Due to delays in software acquisition, experimentation was not conducted, but the experimentation design and scenario development was achieved to be able to conduct experiments once funding is allocation and software is received. Estimated date is March 2023.
- Based on SME input, considerations for common ground control system, and the management of multiple UxSs is as follows:
    - The simplicity in design as there is less time to learn different configurations
    - Positive C2 confirmation – confirmation that the operator is tasking the appropriate UxS
    - Needing onboard autonomy that allows for airspace management is essential for managing multiple UxSs
    - Need to consider the assignments of operations in UxS management. It is not feasible to have the same person for vehicle and sensor management.
    - Needs for autonomy were identified, with the most important being a steady state pattern in life monitoring, positive ID, and enhanced discrimination of targets.
- Scenario development included having situational awareness using multiple UASs for situational awareness in small city/village, maintaining all angles in location/building of interest as the context changes. Also, using communications in D2 environments for maintaining situational awareness at the strategic level.

Education:

- Student acquisition is in progress for experimentation in the next cycle. Have begun coordination with NSW Warfare Command and Defense Analysis Applied Design for Innovation Program.

Dissemination:
Planned submission to HICSS after completion of experimentation, for HICSS 2024.

Collaboration and Partnership:
There has been a long-standing relationship between Naval Special Warfare and NPS. This partnership will allow for NSW Warfare Command, NSW Group 8 and NSW Special Reconnaissance Team 1 to continue to support further concept employment and experimentation.

Transition:
A proposal has been submitted along with University of Connecticut, New Jersey Institute of Technology, and NRL-MRY to ONR, where the NPS team would be a part of a larger effort exploring the management of multiple, multi-domain UxSs. The proposal, if selected, would be a four-year study. In addition, NSW Warfare Command has expressed interest in potential funding of this type of research due to the alignment with their future roadmap.

O. SUAS-BASED REMOTE SENSING OF SURFACE WAVES AND BREAKING USING AN EO/IR CAMERA SYSTEM

Participants

Principal Investigator (PI): David Ortiz-Suslow, dortizsu@nps.edu

Major Goals

The objective of this project was to develop a sUAS and payload to remotely sense wind-forced wave breaking (or *whitecaps*) over the ocean to better understand the fundamental physical role wave breaking plays in the air-sea coupled system. This has implications for accurate weather and climate forecasting, critical to Naval marine battlespace superiority, operations planning, and ensuring fixed and mobile assets. In addition, breaking waves generate aerosols which impact the refractive properties of the atmosphere, as well as act as scatterers of optical energy. While the microphysics and energy interaction are understood, the generation mechanism of these aerosols and their impacts on the coupled system is less so, and better understanding hinges on improved sampling methodologies. sUAS provide a flexible sampling platform that can observe the ocean, even in denied or hazardous areas and conditions. The goal of this project to develop the capability and methodology and leverage that to pursue further basic and applied research projects.

Accomplishments:

- Extensive research into available systems for both platform and science payload sourcing. For the airframe, the decision was made to use a rotary blade platform because of easy of deployment and recovery, as well as the capability to dwell over preset locations to allow for spatio-temporal analysis. Furthermore, it was determined that the airframe needed to be able to handle strong wind forcing (horizontal winds exceed 10 knts) while make robust samples (via video/photographs) of the surface for at least 30 minutes (not including ferry time to/from station). The Aerosystems West Heavy-Lift Multirotor hexacopter (ASW-HLM) was selected and a contract to build the system was initiated. That contract includes sensor payload integration, onsite multi-day training at the local ASW facility to include hands-on flight and simulator work. In addition, the PI has established a close working relationship with ASW to facilitate future developments and projects involving sUAS.
- In addition, extensive research was done to select the appropriate sensor for this application. A key objective was to be able to capture optical and infrared imagery of the surface simultaneous and co-located. This allows for more robust whitecap detection and analysis, using the varying emissivity of the water and foam surfaces to better contour the extent of the breaking wave. In addition, the IR measurements provides thermal information on the surface that can be leveraged for additional studies. Based on the analysis, the WIRIS Workswell Pro camera system was selected and contract for that acquisition was executed. In addition to the camera, a compatible gimbal system was acquired by the Gov't and is currently in possession by the PI. While the original plan was to borrow a

colleague's, that unit became unavailable; this acquisition gives the PI more flexibility to achieve the experimental aspects of the project.

- The PI conducted a site visit of ASW in October of this year to interface with ASW and check on the status of the airframe build. Final delivery is expected by end of CY22.
- In addition to acquisition, the PI has done background research on available methods for wave breaking detection and analysis. This work informed the decision-making on the airframe and science payload and will help with developing the analytical tools once data collection has occurred.
- The PI has reached out to NRL scientists running the Coastal Environment Observation Station (CEOBS) to discuss collaboration on using their atmospheric sensing capability to augment the experimental objectives of the project. These data will provide context to the ocean surface measurements from the airframe and in-water measurements planned for the experimental phase. CEOBS is located at the Monterey Bay Academy where NPS have a COA to operate sUAS. These preliminary discussions have been successful, and the PI will be coordinating this with the NRL contact, Dr. Jerome Schmidt, once the experimental plans are finalized.
- The PI has completed all necessary trainings, etc. to be an approved sUAS operator and the ASW copter and science payload have been reviewed and included in the NPS sUAS community register.
- This past summer, the PI participated in an ONR MURI field campaign for the Fog and Turbulence Interaction in the Marine Atmosphere (FATIMA) project and leveraged this opportunity to deploy 3 EO/IR cameras on a large research vessel for 30 days. The data set acquired will be used to jump start development of the tools needed to analyze wave breaking via image processing techniques.
- The PI has joined the CRUSER and sUAS communities at NPS and will interface with these groups to advance the objectives of the project.

Education:
The PI is actively searching for a suitable student to participate in this project once the experimental phase begins.

Dissemination:
Given the current phase of the project, the PI has no dissemination to report.

Collaboration and Partnership:
Collaborations and partnerships with internal and external groups are being explored.

Transition:
There have been significant challenges to acquisition of the airframe and science payload throughout the period of performance. At the time of reporting, those issues have been overcome but the PI is currently waiting for (1) final delivery of a complete airframe (expected end of CY22), (2) delivery of sensor payload (expected end of CY22), and (3) final integration of payload to the copter by ASW (expected beginning of CY23). These delays and challenges have involved a significant amount of the PI's time, but limited the

ability to progress to the experimental and analysis phase of the project. Further support from CRUSER in FY23 has been proposed in order to achieve those aspects of the work. The PI will continue to explore possibilities and opportunities to leverage enhanced capabilities to garner extramural funding. Looking forward, the PI is an investigator on the funded ONR project: Radar and Electromagnetic wave Ducting in the Stable Atmosphere (REDSAW), which has extensive field work planned in 2024. The PI is exploring with the project lead the possibility of augment the sampling plan to include the copter and payload developed through this project.
In addition, the PI was recently awarded an ONR Young Investigator Program award focused on wave breaking and air-sea interaction, which would benefit from sUAS-based sampling of wave breaking statistics.

P. WHO MAKES JOHNNY 5 COME ALIVE? USING DIVERSE PERSPECTIVES TO DRIVE REQUIREMENTS FOR HUMAN-ROBOT TEAMS

Participants

- Principal Investigator (PI): Douglas L. Van Bossuyt <douglas.vanbossuyt@nps.edu>
- Co-PIs:
  - Robert Semmens – West Point
  - Kristen Fletcher
  - Britta Hale
  - Kristin Weger – University of Alabama Huntsville
  - Bryan Mesmer – University of Alabama Huntsville
  - Nicholaos Jones – University of Alabama Huntsville
  - Amy Guerin – University of Alabama Huntsville
- Students:
  - LT Devon Florendo - 580
  - CPT Stergios Barmpas (GR) – 580
  - LT Peter Dowling – 580
  - CPT Mehmet Bahadir – 580
  - LT. Jamie Dubyoski - 580

Major Goals

The objective of this work was to support the "coherence to accelerate development, operationalization, and adoption" of autonomous systems (AS) as described in the DON's S&T Strategy for Intelligent Autonomous Systems. We hypothesized that diverse teams will create better requirements, which will lead to better systems.

We undertook two related efforts. First, we conducted an experiment that asked participants to create requirements for an AS. Then the participants were exposed to a list of requirements generated by individuals with diverse backgrounds. After that, we asked the participant to update their requirements, considering the requirements generated by others. These changes will allow us to understand the practical impact of diverse ideas on an individual when considering requirements. This work is still ongoing at the University of Alabama Huntsville.

In our second effort, we attempted to lay the groundwork to work with USNA and USMA to observe teams working with autonomous systems in a contested environment in a future year. Currently, the Office of Naval Research sponsors a competition between USMA and USNA twice a year, where midshipmen and cadets employ robots in a force-on-force exercise at Quantico. CDR Chris Wolfgeher at USNA, and Misha Novitsky and Rob Semmens at USMA welcomed our team to observe their exercises. In the future, we will work to be prepared to qualitatively understand how the participants generate requirements for AS, and after using them in a force–on-force exercise, how they update their requirements in a future year and from a different funding source. This may provide the impact of practical experience on AS requirements development. From there, in a future year and under different funding we plan to work with design teams at NPS,

USAFA, and UAH to gain reactions to the requirements evolution that come from the USNA-USMA exercise. This will provide another source of diverse perspectives.

Accomplishments:

- We worked on developing the survey instruments to better understand the practical impact of diverse ideas on requirements. This effort is still ongoing due to when the funding reached the University of Alabama Huntsville.
- We attended a field exercise to observe Midshipmen and Cadets in the field. This laid the groundwork for future engagements. Further work was delayed due to the transition of the original PI of this research.
- We published research developed from this and previous CRUSER-funded projects.

Education:

- Two NPS Capstone projects were supported by this effort including:
    - CPT. Stergios Barmpas, LT. Peter Sebastian Dowling, LT. Devon L. Florendo, Mounted Tracking Launcher, 580 Cohort, Naval Postgraduate School June 2022 - March 2023
    - CPT. Mehmet Bahadir, LT. Jamie Dubyoski, Mounted Tracking Launcher (MTL), 580 Cohort, Naval Postgraduate School June 2021 - March 2022
        - Note these two students continued to June 2022 working with us under a directed study course

Dissemination:

The following was published as part of this research:

- K Weger, L. Matsuyama, R. Zimmermann, B. Mesmer, D.L. Van Bossuyt, R. Semmens, C. Eaton. Insight into the Acceptance and Adoption of Autonomous Systems by Military Personnel. International Journal of Human-Computer Interaction. Special Issue on AI, Decision-Making, and the Impact on Humans. https://www.tandfonline.com/doi/full/10.1080/10447318.2022.2086033. June 2022.
- H.M. Barr, R.C. Smitherman, B. Mesmer, K. Weger, D.L. Van Bossuyt, R. Semmens, N.L. Tenhundfeld. Use, Acceptance, and Adoption of Automated Systems with Intrinsic and Extrinsic Motivation Based Incentive Mechanisms. IEEE Systems and Information Engineering Design Symposium, https://doi.org/10.1109/SIEDS55548.2022.9799319. SIEDS 2022.
- D.L. Van Bossuyt, B. Hale, R. Arlitt, N. Papakonstantinou. Multi-Mission Engineering with Zero Trust: a Modeling Methodology and Application to Contested Offshore Wind Farms. 2022 ASME International Design Engineering Technical Conferences & Computers and Information in Engineering Conference}, IDETC/CIE 2022.[2]

Collaboration and Partnership:

The University of Alabama Huntsville has been integral to this research. They have the psychologists and industrial engineers necessary to conduct parts of the research. This collaboration has been ongoing for four years across multiple projects funded by multiple organizations within and external to DoD.

Transition:
There are several agencies that are interested in how to develop autonomous systems, including the Office of Naval Research, the Army Research Laboratory, and the Human-Systems Integration Division at NASA. The team has interacted with parts of all of these organizations, and have received small funding from NASA related to previous efforts. A proposal is currently pending with NASA Marshall Space Flight Center. The team is continuing to pursue funding with the Army Research Laboratory and is looking elsewhere within DoD for further funding to continue the effort.

III. COMMUNITY OF INTEREST

A. MEMBERSHIP

The CRUSER community of interest (COI) membership grew slightly to ~3,000 members as of December 2022. The membership breakdown is 54% general population, 26% education, 18% military, and 2% government.

B. MONTHLY MEETING PROGRAM

CRUSER holds a monthly community meeting generally on the first Monday or the month at the noon hour. In 2022, the meetings were held virtually using Zoom for Government. These monthly meetings are intended as information sharing forums for the entire CRUSER community of interest, and each month feature presentations from CRUSER funded researchers, CRUSER supported NPS thesis students, or any member of the non-resident CRUSER community that has a significant topic to share. In 2022, there were 12 monthly CRUSER meetings featuring 21 presentations.

Month	Presentation Title(s)	Presenter(s)
January	Naval Research Global Overview - Science Advisor Program	Joanne Pilcher, Global Science Advisor Program Director (Acting), ONR Global NAVIFOR Science Advisor, Naval Information Forces, ONR
February	Academic Venture Exchange - Central Coast Tech Bridge SBIR/STTR Opportunities	Megen Schlesinger, Deputy Director, NavalX Central Coast (C2) Tech Bridge and Travis Linderman, Managing Director
March	NPS Robotics Engineering Graduate Certificate Design Challenge for Discovery Day at NPS	Dr. Brian Bingham, Director, CRUSER, Jessica Herman, MAE Dept, and Marianna Jones, Systems Engineering Dept, NPS Dr. Mara Orescanin, Dept of Oceanography, NPS
April	Naval Warfare Studies Institute (NWSI) Brief Nimitz Research Group Brief	Col Randy Pugh, Senior U.S. Marine Corps Service Rep, NPS Christopher Adams, Director, MAE Dept, NPS

May	Advancing Legal Clarity for Unmanned and Autonomous Systems Rigid Formation Control of Unmanned Surface Vehicles	Kristen Fletcher, Faculty Associate-Research and Marina Lesse, Faculty Associate-Research, Energy Academic Group, NPS MIDN 1/c Jennifer Nguyen, US Naval Academy
June	Aqua-Quad, Progress and Challenges Countering Uncrewed Aircraft Systems with the Detachable Drone Hijacker	Dr. Kevin Jones, Dept. of Mechanical and Aerospace Engineering, NPS Capt. Christian Thiessen, USMC, Dr. Kevin Jones, Dept. of Mechanical and Aerospace Engineering, Dr. Britta Hale, Dept. of Computer Science, Dr. Douglas Van Bossuyt, Dept. of Systems Engineering, NPS
July	Enabling Partner Force Innovation as a Form of Security Force Assistance: The Case of COTS Drones Robotics SRI International	Dr. Leo Blanken, MAJ Patrick Foley, Michael Stevens, Dept. of Defense Analysis and Dr. Kevin Jones, Dept. of Mechanical and Aerospace Engineering, NPS Alexander Kernbaum
August	Advanced Autonomous Capabilities Assistant Program Manager - Rapid Autonomy Integration Lab - An Approach to Unmanned Maritime Software Development PSAP: Persistent Smart Acoustic Profiler	LCDR Jessica Olena - PMS 406 Unmanned Maritime Systems John Joseph, Dept of Oceanography, NPS
September	CRUSER SEED Research Program - Call for Proposals US Naval Research Laboratory - Laboratory for Autonomous Systems Research	Dr. Mara Orescanin, Dept of Oceanography, NPS Dr. Signe A. Redfield, Director, Laboratory for Autonomous Systems Research (LASR),
October	NWSI Warfare Innovation Continuum (WIC) Workshop 2022 “Future Hybrid Force" Cooperative Control of Multiple	Ms. Lyla Englehorn, NWSI Concepts Branch Lead, NPS LT Heuback, Dept of Mechanical Engineering Student, NPS

	Autonomous Surface Vessels in a GPS-Denied Environment	
November	Interactive Synthetic Environment (ISE) to Evaluate Zero-Carbon UAS Launch Platforms in the Arctic	Christian Fitzpatrick, Dept of Computer Science, NPS, Kristen Fletcher, Energy Academic Group, NPS, Marina Lesse, Energy Academic Group, NPS and Capt. Tim Socha, Student,
December	CAMRE (Consortium for Additive Manufacturing, Research and Education) Group Overview Development of Operational Scenarios for Hydrogen-Powered UAVs	Garth Hobson, Emre Gunduz, and Walter Smith, MAE Dept, NPS, Amela Sadagic, MOVES Institute, NPS LT Chase Smeeks, Student, NPS

IV. RESEARCH INFRASTRUCTURE

A. JOINT INTERAGENCY FIELD EXPERIMENTATION

Overview
The JIFX team leads experimentation in alternative methods to enable rapid technological development by cultivating a community of interest and hosting broadly scoped quarterly collaborative field events which enable DoD, US government, and allied stakeholders to identify, influence, and accelerate early-stage technology development that address national and collective security challenges.
In 2022, JIFX hosted four quarterly events at both the NPS Field Laboratory at Camp Roberts Army National Guard Base and the Sea, Land, Air Military Research (SLAMR) Facility in Monterey, CA. In 2021, JIFX hosted X experiments and X participants.

JIFX 2022 Dates:
- JIFX 22-2: 14 – 18 February 2022
- JIFX 22-3: 16 – 20 May 2022
- JIFX 22-4: 15 – 19 August 2022
- JIFX 23-1: 7 – 9 November 2022

Primary Contacts
- Mike Richardson, JIFX Director, mrichard@nps.edu
- Ashley Hobson, JIFX Event Manager, ashobson@nps.edu
- Aurelio Monarrez, JIFX Flight Operations: amonarre@nps.edu
- Joseph Lukefahr, JIFX Network Operations: joseph.lukefahr.ctr@nps.edu
- Jonathan Coon, JIFX Data Management: Jonathan.coon@nps.edu

Accomplishments:
- In 2021, the JIFX program was able to maintain high-quality experimentation events despite the global changes due to the Pandemic. The program was adapted to host virtual events when in-person events were not practical and in the second half of 2021, the program returned to in-person events.
- In 2021, the JIFX program added the Sea, Land, and Air Military Research (SLAMR) facility as a secondary location for experiments during JIFX events. The unique SLAMR facility allows for experiments to utilize the aquatic tanks in extremely close proximity to the NPS campus. This also increased NPS student participation during the event as they were able to easily travel to the SLAMR facility.

Education:
In 2021, the JIFX program worked closely with students from several Naval Postgraduate School educational curriculums including 697 - Applied Design for Innovation; 595 - Information Warfare; and 474 - Doctor of Philosophy in Information Sciences.

The team further supported research conducted by NPS' Center for Autonomous Vehicle Research (CAVR), California State University-Bakersfield Fabrication Lab as well as the University of Hawaii-Applied Research Laboratory (UH-ARL).
Finally, JIFX team members hosted and supported to the 2021 Northern California-Monterey Regional Marine Advanced Technology Education Inspiration for Innovation (MATE II) Remotely Operated Vehicle (ROV) competition at the SLAMR Facility. MATE II is a National Science Foundation sponsored STEM Education and Workforce development program.

Dissemination:
JIFX 22-2 Quicklook
JIFX 22-3 Quicklook
JIFX 22-4 Quicklook
JIFX 23-1 Quicklook

Collaboration and Partnership:
The following companies and organizations participated in a JIFX event in 2021:

JIFX will continue into 2023 with the following events:

B. SEA, LAND, AIR MILITARY RESEARCH (SLAMR) INITIATIVE

C. ROBODOJO

V. EDUCATION

A. STUDENT TRAVEL

- Primary Point of Contact: Jean Ferreira, Operations Manager

Overview

As an incentive for NPS active-duty students to engage broadly with academic, defense and industry communities during their studies, CRUSER continues to support student travel when related to robotics and autonomous systems. Students often take advantage of this opportunity to participate in field experimentation, make site visits to sponsors, interview stakeholders or present their work at conferences and workshops.

Accomplishments

During 2022, student members executed 24 travel events, with a total cost of $44,590.86, related to CRUSER research projects.

Table 2: Student Travel in 2022

Destination	Purpose
Twenty-Nine Palms, CA	MCLOG meeting re: unmanned logistics systems in advance base ops
Camp Roberts, CA	Meeting with JVAB re: countering RF hopping between UAV & ground station
Ridgecrest & Tehachapi, CA	Tour Edwards AFB & China Lake F22/F35 testing & weapon development
Tehachapi, CA	Experimental testing at Rocketry Launch Site
Tehachapi, CA	Experimental testing at Rocketry Launch Site
San Diego, CA	Testing of security app on USV interops with ScanEagle
San Diego, CA	Testing of security app on USV interops with ScanEagle
Monterey, CA	USNA CDT performed 8-week internship at NPS SE Lab
Tooele, UT	Experimental testing for MCWL OPF-IL Equipment
Crane, IN	Exercise Keep Summer Safe: coordination of USVs, UAVs, ULVs
Crane, IN	Exercise Keep Summer Safe: coordination of USVs, UAVs, ULVs
Tehachapi, CA	Experimental Testing at Rocketry Launch Site
Tehachapi, CA	Experimental Testing at Rocketry Launch Site
Camp Roberts, CA	Observation of JIFX Experiments at McMillan Airfield
Camp Roberts, CA	Observation of JIFX Experiments at McMillan Airfield
Tehachapi, CA	Experimental Testing at Rocketry Launch Site
Tehachapi, CA	Experimental Testing at Rocketry Launch Site

Tehachapi, CA	Experimental Testing at Rocketry Launch Site
Colorado Springs, CO	Arctic solutions for SOF with potential use of autonomous systems
Colorado Springs, CO	Arctic solutions for SOF with potential use of autonomous systems
Colorado Springs, CO	Arctic solutions for SOF with potential use of autonomous systems
Sydney, Australia	Served as Judge at 2022 Maritime RobotX Challenge
Hanko, Finland	Thesis Research: data collection at ASV EXERCISE Freezing Winds
Tehachapi, CA	Experimental Testing at Rocketry Launch Site

B. ROBOTICS ENGINEERING GRADUATE CERTIFICATE

VI. CONCEPT GENERATION

A. WARFARE INNOVATION CONTINUUM

VII. STEM ACTIVITIES

INITIAL DISTRIBUTION LIST

Defense Technical Information Center
Ft. Belvoir, Virginia

Dudley Knox Library
Naval Postgraduate School
Monterey, California

Research Sponsored Programs Office, Code 41
Naval Postgraduate School
Monterey, CA 93943

Deputy Undersecretary of the Navy – PPOI
100 Navy Pentagon Room 5E171
Washington, DC 20350

Office of Naval Research
One Liberty Center, 875 North Randolph Street, Suite 1425
Arlington, VA 22203